Renewable and Sustainable Energy Reviews 14 (2010) 73–92

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biomass gasification for decentralized power generation: The Indian perspective

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ARTICLE INFO

Article history:
Received 10 June 2009
Accepted 14 July 2009

Keywords:
Biomass gasification
Biomass gasifiers
Rural electrification
Decentralized power generation

ABSTRACT

This article attempts to highlight the technical and economical issues related to decentralized power generation in India using biomass gasification. Biomass-based energy has several distinct advantages such as wide availability and uniform distribution that puts it ahead among the renewable energy options for India. The estimated potential of power generation through renewable sources in India is 85 GW with biomass power contributing approximately 20 GW. Especially, in the remote areas and hilly terrains of India, biomass gasification-based power generation offers a highly viable solution for meeting energy demands of small villages and hamlets, which would not only make them independent but will also reduce burden on state electricity boards. This paper reviews various technical options for biomass gasification-based low-, medium- and large-scale power generation. We essentially discuss the merits and demerits (operational and other problems) of different systems. Further, we also deal with economics of these systems and discuss principal factors influencing the viability of the biomass-based power generation. Finally, we review some case studies of biomass-based power generation for meeting energy needs, both thermal and electrical.

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.07.034

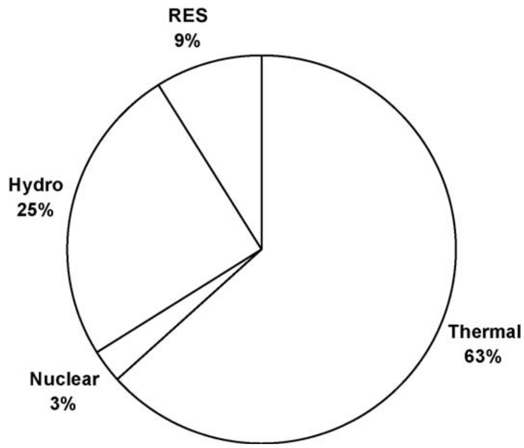

Fig. 1. Contribution of various sources to total power generation in India.

1. Introduction

For a developing country like India, energy is the fundamental input for economic growth. The current target of economy growth rate is 10% and the energy demand in various sectors such as agriculture, industry, transport, commercial and domestic is fast rising. Electricity is perhaps the most vital form of energy input required for infrastructural development of the country in agriculture and industry, and it also plays a critical role in socio-economic development. The total installed capacity of power generation through various sources (as on February 2009) is about 147.72 GW with gross generation of more than 700 billion kWh [1]. The distribution of power generation through different sources, however, is uneven as shown in Fig. 1. The thermal power contribution to this is ~63% followed by hydropower contributing ~25%. The share of nuclear power is the smallest with ~3%, and the power generation through renewable sources contributes the remaining ~9% [2,3]. The exact distribution of the power scenario in various states of India is given in Table 1. After grouping of the states into various regions, the distribution of power generation is shown in Fig. 2. The reason behind this uneven distribution is that India has over 200 billions tons of coal deposits. Thus, the generation is mainly dominated by coal-based thermal power plants. However, the coal reserves are mainly concentrated in the north and northeastern states of India and not uniformly spread in the country (refer to Table 2 for distribution of coal deposits in various states). Presently the generation capacity is far insufficient to meet the demands. Although per capita electricity consumption in India during the past 5 years has risen from 566.7 to 704.2 kWh (refer to Fig. 3), it is still far below the global average of 2000 kWh [4]. Currently, the estimated average gap between supply and demand of electricity (peak demand) is about 14%. The transmission and distribution losses are estimated between 26 and 32%. With rapid urbanization and industrialization, this gap is bound to rise fast. In addition, rural electrification has also posed a major challenge to India's growth. The major hurdles in rural electrification are extension of the grid to remote areas, large transmission losses and low peak loads due to small and isolated population [5–7]. Unlike urban areas, the primary electricity need of the rural population is for domestic lighting, running of irrigation pumps and small-scale commercial activities such as floor mill and other rural industries. The National Electricity Policy (NEP) announced by Government of India along with other activities such as *Rajiv Gandhi Grameen Vidyutikaran Yojana* has given high priority to rural electrification. The primary aim of this is to achieve complete rural electrification by 2010. Table 3 gives a more detailed account of the status of rural electrification in various states of India. In order to present a realistic picture of rural electrification, Ministry of Power of Government of India has modified the definition of an "electrified village". Earlier definition of electrified village was "a village in which electricity is being used within its revenue area for any purpose whatsoever". In 2004–2005, this definition was given four important criteria as follows [8,9]:

1. Provision of basic infrastructure such as distribution transformer and distribution lines in the inhabited locality.
2. Provision of electricity to public places like schools, *Panchayat* offices, health centers, etc.
3. Access of electricity to a minimum of 10% households in the village.
4. Compulsory certification from *Gram Panchayat* regarding completion of village electrification.

Although the overall rural electrification stands at an impressive figure of 82%, the actual number of households accessing the electricity is mere 44% [10]. Presently, the rural electrification is growing at a rate of 3–6% annually [9,11]. In very remote areas where extensive of grid is not feasible, decentralized power generation through renewable sources offers a viable solution for meeting the electricity needs of the local population [12–14]. In fact, the NEP insists on use of both conventional and renewable sources of electricity generation, as long as they are economically viable. In order to reduce load on grid and state electricity boards, NEP emphasizes use of renewable energy even in areas with access to grid, provided renewable sources are as economic as conventional ones. Options for decentralized generation through renewable sources for are wind energy systems, solar photovoltaics, biomass gasifiers and small hydropower systems, etc. [10]. The most economic option depends on the location of area and natural resources available [15]. Another motive for exploration of renewable sources for power generation is the fluctuating economy of the conventional sources. The principal sources of energy are fossil fuels such as coal, oil and gas. However, the prices of oil and gas are highly fluctuating and there is also a fear of their acute shortage in the future. Moreover, emancipated use of fossil fuels also causes environmental pollution problems such as emission of greenhouse gases. Thus, there is an urgent need for harnessing the large potential of renewable energy sources in a planned and strategic manner to reduce the gap between demand and supply. Promotion of energy conservation and increased use of renewable energy are the twin planks of a sustainable energy supply [14,16]. In this paper, we have attempted to review the feasibility of the decentralized power generation through biomass gasification and technical and economic aspects related to this. The estimated annual biomass production in India is 200 million tons, which (unlike coal) is distributed almost evenly in the country (greater details about this are given in section 3). This is equivalent of 20 GW of installed capacity. In addition, agro-residues and woody bio-residues from wastelands (estimated at 60 million hectares) could add another 100–300 million tons, which amount to 45 GW of installed capacity. However, the total installed capacity of biomass-based power generation (inclusive of bagasse and non-bagasse cogeneration and biomass gasifiers; as of September 2007) is 838 MW [17]. This capacity is mainly through cogeneration (692.3 MW through bagasse fired boilers), which is an inefficient method of utilization of the biomass energy. This indicates that the vast potential of biomass power remains almost unused, and there is an urgent need of utilization of this resource through more efficient technologies such as biomass gasification.

Table 1
Power scenario in various states of India (installed capacity in MW of power utilities including allocated shares in joint and central sector utilities).

State	Mode-wise breakup				Nuclear	Hydro (renewable)	Renewable energy sources	Grand total
	Thermal			Total thermal				
	Coal	Gas	Diesel					
States in northern region								
Delhi	2240.50	804.70	0.00	3045.20	47.08	585.06	0.00	3677.34
Haryana	2518.07	532.04	3.92	3054.03	76.16	1331.40	68.70	4530.29
Himachal	95.41	60.89	0.13	156.43	14.08	1540.84	185.12	1896.47
Jammu and Kashmir	198.59	302.09	8.94	509.62	68.00	1469.50	111.83	2158.95
Punjab	3176.21	259.72	0.00	3435.93	151.04	3031.57	161.47	6780.01
Rajasthan	3112.49	661.54	0.00	3774.03	469.00	1456.82	726.30	6426.15
Uttar Pradesh	6493.31	541.16	0.00	7034.47	203.72	1605.49	402.98	9246.66
Uttarakhand	232.80	68.25	0.00	301.05	16.28	1955.73	109.97	2383.03
Chandigarh	26.51	15.07	0.00	41.58	4.84	47.04	0.00	93.46
Central (unallocated)	713.61	285.73	0.00	999.34	129.80	401.70	0.00	1530.84
Grand total for northern region	18807.50	3531.19	12.99	22351.68	1180.00	13425.15	1766.37	38723.20
States in western region								
Goa	279.18	48.00	0.00	327.18	0.00	0.00	30.05	357.23
Daman and Diu	64.99	4.13	0.00	69.12	1.98	0.00	0.00	71.10
Gujarat	6349.79	2748.62	17.48	9115.89	825.00	772.00	1397.50	12110.39
Madhya Pradesh	4281.10	252.91	0.00	4534.01	92.88	3223.67	262.71	8113.27
Chhattisgarh	3312.90	0.00	0.00	3312.90	0.00	120.00	174.15	3607.05
Maharashtra	10112.00	3709.28	0.00	13821.28	852.06	3332.83	2159.21	20165.38
Dadra and Nagar Haveli	52.19	26.61	0.00	78.80	1.98	0.00	0.00	80.78
Central (unallocated)	950.35	193.67	0.00	1144.02	66.10	0.00	0.00	1210.12
Grand total for western region	25402.50	6600.72	17.48	32403.20	1840.00	7448.50	4023.62	45715.32
States in southern region								
Andhra Pradesh	5719.88	1603.40	36.80	7360.08	37.41	3572.93	668.66	11639.08
Karnataka	3302.67	220.00	234.42	3757.09	190.90	3518.20	1880.54	9346.73
Kerala	765.38	524.00	256.44	1545.82	80.09	1769.10	119.04	3514.05
Tamil Nadu	5519.81	1026.40	411.66	6957.87	657.39	2093.95	4379.64	14088.85
NLC	100.17	0.00	0.00	100.17	0.00	0.00	0.00	100.17
Pondicherry	207.01	32.50	0.00	239.51	17.09	0.00	0.02	256.62
Central (unallocated)	1067.58	0.00	0.00	1067.58	117.12	0.00	0.00	1184.70
Grand total for southern region	16682.50	3646.10	939.32	21267.92	1100.00	10724.18	7047.90	40130.20
States in eastern region								
Bihar	1846.59	0.00	0.00	1846.59	0.00	73.00	50.40	1969.99
Jharkhand	1972.52	0.00	0.00	1972.52	0.00	176.00	4.05	2152.57
West Bengal	6357.94	100.00	12.20	6470.14	0.00	1162.00	99.55	7731.69
DVC	3100.00	90.00	0.00	3190.00	0.00	196.00	0.00	3386.00
Orissa	1865.23	0.00	0.00	1865.23	0.00	2174.93	32.30	4072.46
Sikkim	1232.12	0.00	0.00	1232.12	0.00	77.00	0.00	1309.12
Central (unallocated)	1232.12	0.00	0.00	1232.12	0.00	77.00	0.00	1309.12
Grand total for eastern region	16446.38	190.00	17.20	16653.58	0.00	3933.93	227.41	20814.92
States in northeastern region								
Assam	60.00	441.50	20.69	522.19	0.00	431.00	27.11	980.30
Arunachal Pradesh	0.00	21.00	15.88	36.88	0.00	98.00	45.26	180.14
Meghalaya	0.00	26.00	2.05	28.05	0.00	229.00	31.03	288.08
Tripura	0.00	160.50	4.85	165.35	0.00	62.00	16.01	243.36
Manipur	0.00	26.00	45.41	71.41	0.00	81.00	5.45	157.86
Nagaland	0.00	19.00	2.00	21.00	0.00	53.00	28.67	102.67
Mizoram	0.00	16.00	51.86	67.86	0.00	34.00	17.47	119.33
Central (unallocated)	0.00	56.00	0.00	56.00	0.00	128.00	0.00	184.00
Grand total for noreastern region	60.00	766.00	142.74	968.74	0.00	1116.00	171.00	2255.74
Islands								
Andaman and Nicobar	0.00	0.00	60.05	60.05	0.00	0.00	5.35	65.40
Lakshadweep	0.00	0.00	9.97	9.97	0.00	0.00	0.76	10.73
Grand total for islands	0.00	0.00	70.02	70.02	0.00	0.00	6.11	76.13

Source: [1].

2. Brief history of renewable energy efforts in India

The main renewable sources are solar energy, wind energy, small hydropower, biomass, biogas and energy recovery from municipal and industrial wastes. India has tremendous natural resources that have potential of all of the above-mentioned renewable energy sources. The advantages of renewable energy are: (1) complete perpetuity; (2) local availability without needing major transport; (3) modularity, i.e. economy is independent of scale; and (4) non-polluting nature (carbon neutrality). Especially,

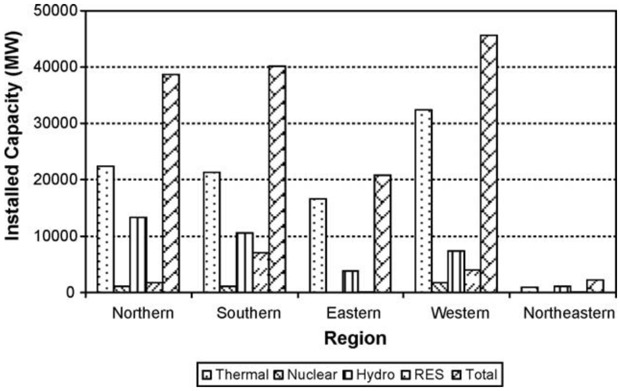

Fig. 2. Distribution of power generation in different regions of India.

Table 2
Distribution of coal reserves in India.

S. No.	State	Total reserves[a] (MMT)
1.	Andhra Pradesh	17,715
2.	Arunachal Pradesh	90
3.	Assam	375
4.	Bihar	160
5.	Chhattisgarh	41,450
6.	Jharkhand	74,392
7.	Madhya Pradesh	20,346
8.	Maharashtra	9,670
9.	Meghalaya	460
10.	Nagaland	20
11.	Orissa	63,223
12.	Sikkim	73
13.	Uttar Pradesh	1,062
14.	West Bengal	28,335
	Grand total	257,381

Source: [21].
[a] Total capacity including proven, indicated and inferred reserves.

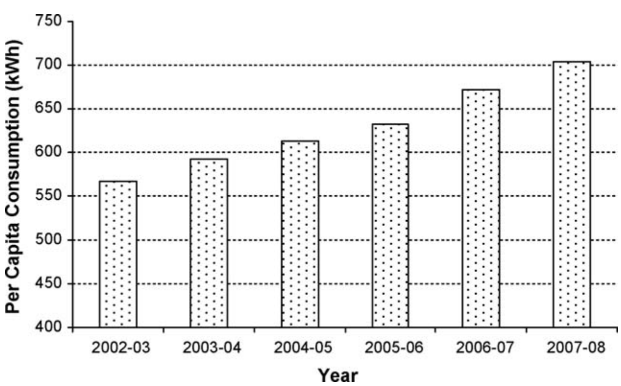

Fig. 3. Per capita power consumption in India.

for remote villages located in hilly and mountainous regions, where transmission of electricity through power grid is difficult, renewable energy is the only option for meeting energy requirements for cooking, heating and domestic and street lighting. Decentralized electricity generation through renewable sources even in urban areas gives a viable solution to the shortage and increasing cost of electricity. Ministry of New and Renewable Energy (MNRE) of Government of India has implemented comprehensive programs for the development and utilization of various renewable energy sources in the country.

The first ever endeavor in renewable energy in India dates back to 1897 in which a small hydropower project of 130 kW capacity was implemented at Sidrapong in Darjeeling [9,18]. This was followed by two more hydro projects of 40 and 50 kW capacity each at Chamba and Jubbal installed in 1902 and 1911, respectively. The facility of transmission lines did not exit at that time, and hence, power generated through these projects was mainly utilized for meeting the local energy demands.

2.1. Ministry of New and Renewable Energy

In the modern independent India, efforts in renewable energy began in 1981 during 6th 5-year plan (1980–1985) with establishment of Commission for Additional Sources of Energy (CASE) as a part of Department of Science and Technology (DST). This commission was in line with Atomic Energy Commission and was bestowed the responsibility of developing renewable energy. In 1981, Government of India created Department of Non-conventional Energy Sources (DNES) for development, demonstration and application of renewable energy. CASE became a part of this department. In 1982, Ministry of Energy was expanded to include Department of Petroleum and DNES. In 1983, an advisory board on energy was set up to formulate an integrated energy policy covering commercial and noncommercial energy resources. Almost a decade later, DNES was transformed into a full-fledged ministry – Ministry of Non-Conventional Energy Sources (MNES). In October 2006, the MNES was renamed as Ministry of New and Renewable Energy (MNRE). MNRE is the nodal ministry of Government of India (and only of its kind in the world) that handles the matters related to development and promotion of renewable energy in India. In the 6th plan, government encouraged research, design, development, indigenous fabrication and demonstration projects along with stand-alone systems on solar, wind, biomass and biogas (for decentralized power generation) through financial subsidy and incentives. During 7th plan (1985–1990) as well priority was given to solar, thermal, biogas and solar photovoltaic systems for decentralized power generation. In the same period, Indian Renewable Energy Development Agency (IREDA, a financial arm of the MNES) was constituted for exclusive funding for natural renewable energy projects through soft loans. In the 8th plan (1992–1997) Government emphasized on commercialization of the renewable energy technologies and new research and development policy was formulated that allowed industrial participation. Market-oriented approach was adopted for commercial/near-commercial technologies with phasing out of subsidies. In some areas, capital subsidy regime was shifted to interest subsidy system. More fiscal incentives were provided during the 9th plan (1997–2002) such as customs and excise relief, income tax holiday, accelerated depreciation, provision of facilities by state electricity boards for wheeling, banking, buy back and third-party sale at remunerative prices. Resources from external funding agencies such as World Bank, Asian Development Bank, UNDP (United Nations Development Program), GEF (Global Environment Facility) and DANIDA (Danish International Development Agency) were also utilized. The 10th plan emphasized on grid connected power, rural electrification and promotion of renewable energy systems and devices in urban areas. More incentive was given for the demand-driven rather than supply-driven programs and capital subsidies were replaced with subsidies linked with renewable energy generation that encouraged purchase of renewable energy. In the 11th plan (2007–2011), which is being finalized, thrust will be on grid-interactive and distributed renewable power; rural, urban, industrial and commercial applications of renewable energy, R&D for new and emerging technologies through financial and fiscal incentives [19].

2.2. Important policies of Government of India for renewable energy

Some important policies and acts made by the Government regarding renewable energy are listed below [17]:

Table 3
Current status of rural electrification in India.

S. No.	State/union territory	Total inhabited villages[a]	Villages electrified as on 31-01-2009	Percentage of village electrification	Unelectrified villages as on 31-01-2009	No. of connections to rural households[b]
States						
1.	Andhra Pradesh	26,613	26,613	100%	0	3,954,128
2.	Arunachal Pradesh	3863	2195	56.8%	1668	76,407
3.	Assam	25,124	19,741	78.6%	5383	1,414,828
4.	Bihar	39,015	20,620	52.9%	18,395	6,022,036
5.	Chhattisgarh	19,744	18,877	95.6%	867	1,285,545
6.	Delhi	158	158	100%	0	N.A.
7.	Jharkhand	29,354	9119	31.1%	20,235	2,926,260
8.	Goa	347	347	100%	0	N.A.
9.	Gujarat	18,066	18,014	99.7%	52	1,595,853
10.	Haryana	6764	6764	100%	0	569,686
11.	Himachal Pradesh	17,495	17,183	98.2%	312	36,479
12.	Jammu and Kashmir	6417	6304	98.2%	113	295,221
13.	Karnataka	27,481	27,126	98.7%	355	1,836,403
14.	Kerala	1364	1364	100%	0	23,799
15.	Madhya Pradesh	52,117	50,255	96.3%	1892	2,653,536
16.	Maharashtra	41,095	36,296	88.3%	4799	2,633,742
17.	Manipur	2315	1982	333	85.5%	76,267
18.	Meghalaya	5782	3428	59.3%	2354	188,648
19.	Mizoram	707	570	80.6%	137	44,334
20.	Nagaland	1278	823	64.4%	455	142,992
21.	Orissa	47,529	26,535	55.8%	20,994	4,858,292
22.	Punjab	12,278	12,278	100%	0	405,023
23.	Rajasthan	39,753	27,286	68.3%	12,467	2,230,387
24.	Sikkim	450	425	94.4%	25	28,166
25.	Tamil Nadu	15,400	15,400	100%	0	1,692,235
26.	Tripura	858	491	57.2%	367	228,759
27.	Uttar Pradesh	97,942	86,450	88.3%	11,492	1,694,075
28.	Uttaranchal (Uttarakhand)	15,761	15,213	96.5%	548	357,309
29.	West Bengal	37,945	36,462	96.1%	1483	3,974,005
Total (states)		593,015	488,289	82.3%	104,726	41,244,415
Union territory[c]						
1.	Andaman and Nicobar Islands	501	331	66.1%	170	N.A.
2.	Chandigarh	23	23	100%	0	N.A.
3.	Dadra and Nagar Haveli	70	70	100%	0	N.A.
4.	Daman and Diu	23	23	100%	0	N.A.
5.	Lakshadweep	8	8	100%	0	N.A.
6.	Pondicherry	92	92	100%	0	N.A.
Total (union territories)		717	547	76.3	170	–
Total (all India)		593,732	488,836	82.3%	104,896	41,244,415

Source: [1,2].
[a] As per 2001 census.
[b] Including the connections to households below poverty line (as on March 1, 2009) under *Rajiv Gandhi Gramin Vidyutikaran Yojana*.
[c] Union territories do not participate in the *Rajiv Gandhi Gramin Vidyutikaran Yojana*.

- *Renewable Power Purchase Guideline (1993)*. Through these advisory guidelines, MNRE instructed states a buy back price of Rs. 2.25/kWh for power through renewable sources (5% annual increment) with 1993 as the base year.
- *Integrated Coal Policy (1996)*. The committee on integrated coal policy recommended adoption of coal conservation measures, investment of private capital in the sector, deregulation of coal and coal product prices and setting up of a regulatory board.
- *Energy Conservation Act (2001)*. This act established comprehensive law that adopted standards and procedures and prescribed measures for energy conservation.
- *Electricity Act (2003)*: This act identified the role of renewable energy technologies for supplying power to the utility grid as well as stand-alone system. It stated that central government shall prepare a national electricity and tariff policy for optimal utilization of various resources including renewable sources in consultation with the state government along with quota for the renewables.
- *National Electricity Policy (2005)*. This policy recognized the role of renewable electricity in the areas where grid connectivity was neither cost effective nor feasible.
- *National Tariff Policy (2006)*. Though this policy the State Regulatory Commissions were authorized to decide upon a minimum percentage for purchase of energy from renewable sources taking into account local availability of such resources and its impact on retail tariffs.
- *Rural Electrification Policy (2006)*. This policy had three principal aims, viz. (1) provision of access to electricity to all households by 2009, (2) quality and reliable power supply at a reasonable rate, and (3) minimum consumption of 1 unit per household per day by 2012. It provided for decentralized distributed generation facilities together with local distribution network based on either conventional or renewable sources of electricity generation (whichever suitable and economical). The policy also encouraged utilization of renewable energy even where grid connectivity exists provided it is cost effective.

2.3. State-of-the-art on renewable energy front

In 2007, renewable energy endeavors in India completed 25 years. In these years, there has been a vigorous pursuit of activities relating to research, development, demonstration and fabrication

Table 4
Renewable energy in India at a glance.[a]

S. No.	Source/system	Estimated potential (MW)	Cumulative installed capacity (MW)/number
I. Power from renewables			
A. Grid-interactive renewable power			
1.	Bio-power (agro-residues and plantations)	16,881	560.30
2.	Wind power	45,195	7660.20
3.	Small hydropower (≤25 MW)	15,000	2014.66
4.	Cogeneration bagasse	5000	692.33
5.	Urban waste to energy	2700	55.20
6.	Solar power	–	2.12
	Subtotal (MW)	84,776	10984.81
B. Captive/combined heat and power/distributed renewable power			
7.	Biomass/cogeneration (bagasse)	–	59.00
8.	Biomass gasifier	–	86.53
9.	Energy recovery from waste	–	20.21
	Subtotal (MW)	–	165.74
	Total (A + B)		11150.55
II. Remote village electrification			
1.	Villages	–	3207
2.	Hamlets	–	830
III. Decentralized energy systems			
1.	Family type biogas plants	12 million	3.93 million
2.	Solar photovoltaic programme	20 MW/km^2	
	(i) Street lighting systems (no.)		61,321
	(ii) Home lighting systems (no.)		363,399
	(iii) Solar lanterns (no.)		565,628
	(iv) Solar power plants		2.18 MW
3.	Wind pumps (no.)	–	1180
4.	Solar cookers (no.)	–	0.62 million
5.	Solar water heating system (m^2 collector area)	140 million	2 million
6.	Solar photovoltaic pumps (no.)	–	7068
IV. Other programs			
1.	Energy parks (no.)		505
2.	Aditya solar shops (no.)		268
3.	Battery operated vehicles (no.)		262

Source: [3,17].
[a] Data as of September 30, 2007.

of variety of new technologies suitable for different sectors. Several technologies and devices have been developed and commercialized such as biogas plants, improved *choolhas* (or woodstoves), various solar energy-based devices (for example solar cookers, solar lanterns, street lights, pumps, etc.), wind electricity generators, water pumping wind mills, biomass gasifiers and small hydroelectric devices. Approximately 11 GW of grid-interactive renewable power generating capacity has been produced with major contributions from wind (7660 MW), small hydropower (2015 MW), bio-power (through agro-residues and plantations, 560 MW), bagasse-based cogeneration (693 MW), urban and industrial wastes (55 MW) and solar (2.12 MW). The contribution by renewable sources to the total installed capacity (as of February 2009 [1]) stands at an impressive 9%, and is continuously growing. Government has been providing several financial and promotional incentives. During 2005–2006 loan sanctions from IREDA stood at Rs. 505.83 crore, while in 2006–2007 the sanctions totaled at Rs. 588 crore. Major sectors funded include wind, small hydropower, biomass power, energy efficiency and conservation, solar thermal and biofuels. IREDA has reintroduced the equipment financing scheme of biomass gasifiers for thermal applications (>1000 kWh) for captive use in industry and small hydropower project exceeding station capacity of 25 MW. In 2006–2007, the financing policy was reviewed and new scheme for financing industrial cogeneration was introduced. The target of IREDA for 11th plan is loan sanction of Rs. 5700 crore that would add capacity of 1.75 GW.

Estimated potential of various renewable energy sources and cumulative achievements throughout the country (as on 30 September 2007) have been given in Table 4 [3,17]. The global position of India in generation/utilization of renewable energy sources is notable, and it is likely to get higher in future. For biogas utilization, India ranks 2nd (after China), for wind energy India stands 4th (after Germany, Spain and USA), for small hydropower India ranks 5th while for solar photovoltaic India stands 7th in the world. The financial allocation for the renewable energy has grown from 0.1% in the 6th plan with 28.1% allocation to the energy sector as a whole to 0.48% in the 10th plan with 27.3% allocation to energy sector as a whole.

3. Biomass power in India

Per the Public Utility Regulatory Policies Act (PURPA, 1978) in USA, the word "Biomass" refers to any organic material not derived from fossil fuels. However, in the context of biomass-based power generation, biomass refers to essentially all organic matter that originates from plants – including all land and water-based vegetation such as algae, trees and crop residues. Biomass has been a primary energy source for cooking and heating. It is estimated that if all biomass used in India was substituted by petroleum products, it would require import of 30 MMTPA of crude oil, creating a burden of Rs. 500 billion [20]. In the past few decades, interest in biomass-based energy is increasing due to some distinct

Table 5
Analysis of major biomasses available in northeast region of India.

Biomass	Carbon	Hydrogen	Nitrogen	Oxygen	Ash
(A) Ultimate analysis					
Composition in weight percent (dry basis)					
Bamboo dust	39.88	5.5	0.89	47.92	5.81
Rice husk	37.03	5.25	0.09	40.94	16.69
Bagasse	47	6.5	0	42.5	4
Coconut fiber	45.68	5.89	0.99	44.63	2.81
Saw dust	52.28	5.2	0.47	40.85	1.2

Biomass	Fixed carbon	Volatile matter	Ash
(B) Proximate analysis			
Bamboo dust	9.3	74.2	16.5
Rice husk	13.2	65.3	19.2
Bagasse	11.9	86.3	1.8
Coconut fibre	29.7	66.6	3.7
Saw dust	25.0	72.4	2.6

Source: [77].

advantages it offers: it is renewable, widely available and uniformly distributed, carbon neutral and more economical than other renewable sources such as solar photovoltaics. By the year 2050, 15–30% of world's primary energy could come from biomass. As of now, about 11% of primary energy needs are being met with biomass. The estimates of MNRE [16] indicate that 32% of the total primary energy use in the country is derived from biomass and more than 70% of population is dependent on it for the energy needs. Biomass-based power generation in India is attracting an investment of Rs. 1000 crore each year with generation of more than 700 billion units of electricity and an annual employment of 10 million man-days in rural areas [20].

3.1. Biomass as a coal substitute

As of April 2007, India has over 250 billion tons of coal reserves [21]. The distribution of these coal reserves in various states is given in Table 2. The consumption of coal by various industrial sectors was 492.5 MMT in 2007–2008 (with 363.6 MMT utilized for power generation), while in 2008–2009 consumption stood at 555 MMT (with 416 MMT utilized for power generation). With these consumption rates, the coal reserves are expected to last for the next 200 years [4]. As depicted in Fig. 1, more than 60% of the current electricity generation is through coal-based thermal power plants. Therefore, we must compare the option of biomass-based power to the coal-based power so as to assess the feasibility of biomass route. The typical composition of biomass varies significantly (refer to Table 5 for composition of major biomasses in the northeastern region); however, typically all biomasses contain about 60–80% volatiles and 15–25% fixed carbon. On comparative basis, coal has only 20–30% volatiles and large (50–70%) fixed carbon. Ash and moisture content shows even wider range variation. Rice husk contains about 20% ash while wood has less than 1% ash, whereas moisture content of sugarcane bagasse could be as high as 50% against less than 20% moisture content in rice husk. As a result of this, the LHV of low ash coal (typically in the range 35–40 MJ/kg) is higher than that of biomass (16–18 MJ/kg). However, if the ash content of coal is high ($\sim$30% or so, typical of Indian coal), the LHV of coal (20–22 MJ/kg) is almost same as that of biomass (16–18 MJ/kg). This substantiates substitution of coal by biomass. Moreover, coal deposits are located only in the state of Bihar and northeast. Thus, transportation costs play a major role in coal-based thermal power projects. Biomass, on the other hand, is uniformly and widely distributed in the country.

3.2. Biomass resources and utilization

The major source of biomass in India is the waste and byproducts of agriculture. In 1985–1986, National Productivity Council undertook a comprehensive survey of this massive resource. On the basis of survey of ratios of various crop residues and useful products, an estimate of state-wise and crop-wise residue generation was made. However, the "recoverable" residues showed significant variation as a function of geographical location and harvesting methods. This data has been updated regularly, and for the agricultural production for 2006–2007 the net production of residue could be around 500 million tons, as described in greater detail in Table 6. More recently, Indian Institute of Science Bangalore has also completed MNRE-sponsored project of creating biomass atlas of India and results of this survey are given in Table 7. All of the residue cannot be available for power generation, as it has been utilized for other purposes such as cooking and cattle feed. Further studies indicated that about 15–20% of the agricultural residue can be made available for power generation without affecting the present usage. Survey of I.I.Sc. Bangalore indicates that about 125 MMTPA of biomass could be available for power

Table 6
Estimation of biomass production in India (crop-wise data).[a]

Crop	Main crop production (MMTPA)	Type of residue	Crop to residue ratio	Residue quantity (MMTPA)	Conventional use
Rice	90	Straw	1.3	117	Cattle feed
		Husk	0.3	27	Fuel for small factories
Wheat	80	Straw	1.5	120	Cattle feed
Coarse cereals	30	Straws and husk	1.8	54	Cattle feed and fuel
Sugarcane	320	Bagasse	0.3	96	Captive fuel by sugar plants, raw material for paper manufacture
		Tops	0.05	16	Cattle feed
		Trash	0.07	20	Burnt in fields
Coconut	14 billion nuts	Shell	0.13 kg/nut	0.2	Domestic fuel, raw material for mattresses, carpets, etc.
		Fiber	0.2 kg/nut	2.8	
		Pith	0.2 kg/nut	2.8	No specific use. Usually disposed off
Cotton	3.5	Stalks	3.0	10.5	Domestic fuel
		Gin waste	0.1	0.35	Fuel for brick factories
Oilseeds	20	Straws and husk	1.1	22	–
Pulses	14	Straws	1.3	18	Domestic fuel
Jute	2	Stalks	2.0	4	Fuel for processing tobacco leaves and as domestic fuel
	Grand total			499	

Source: [20].
[a]Agricultural production data is for the year 2006–2007 (Ministry of Agriculture). The residue ratios and conventional uses from reports of Taluka level studies by MNRE (1998–2004).

Table 7
State-wise annual biomass production data and power generation potential (2002–2004).

S. No.	State	Area (kHa)	Crop production (MMTPA)	Biomass generation (MMTPA)	Biomass surplus (MMTPA)	Power potential (MWe)
1.	Andhra Pradesh	6021.5	28.345	21.569	3.948	481.3
2.	Assam	2586.6	5.945	6625.1	1.362	163.1
3.	Bihar	5833.1	13.818	20.442	4.286	530.3
4.	Chhattisgarh	3815.5	6.143	10.124	1.908	220.9
5.	Goa	156.3	0.555	0.929	0.181	22.7
6.	Gujarat	6519.0	20.636	25.471	8.353	1131.1
7.	Haryana	4890.2	13.520	26.581	10.106	1303.5
8.	Himachal Pradesh	710.3	1.329	2.668	0.988	128.0
9.	Jammu and Kashmir	368.7	0.649	1.199	0.238	31.8
10.	Jharkhand	1299.8	1.509	2.191	0.568	66.8
11.	Karnataka	7356.0	38.754	26.949	7.184	1041.3
12.	Kerala	2058.4	9.773	13.073	7.529	1017.9
13.	Madhya Pradesh	9937.0	14.167	28.349	9.284	1240.2
14.	Maharashtra	15542.3	51.665	39.349	12.998	1751.1
15.	Manipur	72.6	0.159	0.319	0.032	4.14
16.	Meghalaya	0.80	0.014	0.042	0.008	1.09
17.	Nagaland	27.1	0.088	0.149	0.027	3.12
18.	Orissa	2436.6	3.633	5.350	1.163	147.3
19.	Punjab	6776.6	31.731	49.988	24.544	3133.9
20.	Rajasthan	10748.5	12.763	25.234	7.420	975.0
21.	Tamil Nadu	2561.5	24.688	17.459	7.401	967.2
22.	Uttar Pradesh	12672.5	46.842	50.622	11.870	1496.6
23.	Uttaranchal	66.4	0.136	0.160	0.052	6.6
24.	West Bengal	5575.6	21.063	23.333	2.968	369.5
	Grand total	107763.0	347.926	398.175	125.046	16234.2

Source: [78].

generation with a potential of 16.23 GW. Moreover, technical improvement in the domestic usage of biomass could yield an additional surplus. For example, domestic cooking stoves (with efficiency $\leq$ 10%) use about 220 million tons of biomass. Even a marginal improvement in this, with new stove models with efficiency of $\sim$20%, can make available an additional surplus biomass of 100 million tons. Even conservative estimate indicate that availability of biomass through agro-residues would in the range 150–160 million tons which is sufficient to sustain 16–18 GW of power generation with plant load factor of 60–80% [20].

The production of sugarcane in India was estimated at about 320 MMT in 2006–2007. Out of this, about 200 MMT is consumed by 550 sugar factories in India. After crushing, this would generate about 60 MMT of wet bagasse (with about 50% moisture content). The total captive consumption of the factories to meet the steam and power demand is approx 50 MMT and rest is utilized for paper manufacture. Task force set by MNRE in 1993 indicated that an additional 3500 MW of electricity can be generated by adopting technically and economically optimum levels of cogeneration. If all of the 320 MMT of sugarcane produced was crushed in large mills, the generated bagasse will have capacity of about 45 MMT of coal that would produce 6000–7000 MW of electricity.

3.3. Conversion of biomass to electricity: technical options

There are essentially six possible technologies for converting biomass to electricity, as depicted in Table 8. Steam engines were considered robust for installation and operation in rural areas. However, this technology suffered major setback due to implementation of the regulations regarding certified operators for the boilers and non-availability of engines. BIGCC (Biomass Integrated Gasification Combined Cycle) with steam-injected gas turbine was expected to have much higher conversion efficiency. But development of this technology was not marked. Most of the BIG

Table 8
Comparative evaluation of technical options for biomass conversion to electricity.

Technology	Efficiency	Relative capital cost per kW	Merits	Limitations
1. Gasifier with generator coupled to IC engine (with producer gas)	15–22%	1.0	Low cost and simple construction	High maintenance for engine, fuel specificity, suitable for size up to 250 kW
2. Biomass boiler-steam engine	<10%	1.5–2.0	Robust design, biomass flexibility, low maintenance costs	Low efficiency, not suitable for installation and operation in rural and remote areas
3. Biomass boiler-steam turbine	15–24%	1.1–1.3	Relatively high efficiency, robust design, biomass flexibility	Economically feasible for capacity of about 5 MW or higher; thus, unsuitable for small to medium-scale application for remote rural areas
4. BIGCC (Biomass Integrated Gasification Combined Cycle) with either steam or gas turbine	45–55%	2.0–3.0	High efficiency	Complex design, yet to be demonstrated for biomass (under R&D)
5. Biomethanation followed by IC engine (with methane)	20–25%	Under R&D	Low engine maintenance due to purer and cleaner gas, simple design, construction and operation	Yet to be demonstrated (under R&D)
6. External combustion engines	20–30%	1.5–2.0	Flexibility in biomass, high efficiency	Yet to be demonstrated (under R&D)

Source: [20].

Table 9A
List of installation of gasifiers (based on I.I.Sc. Technology) for various applications.

S. No.	Location	Capacity (kWe)	Function	Biomass employed
Industrial applications				
1.	Sriguru Tea Estate, Coonoor, Tamil Nadu	90	Tea leaves drying	Wood
2.	Agrobiochem Pvt. Ltd., Harihar, Karnataka	250 (installed 1998), 450 (installed 2000)	Drying of marigold leaves	Juliflora prosopis
Agricultural applications				
1.	Bethamangala, Kolar district	50	Pumping water from bore-wells	Wood
2.	Farm house, Chennarayapatna	50	Irrigation	Wood
Village electrification				
1.	Hosahalli, Karnataka	50	Domestic and street lighting, drinking water, grinding machines, water irrigation	Pieces from different species of agro-residues
2.	Hanumanthanagara, Karnataka	50		
Industrial applications				
1.	Desi Power Orchcha Pvt. Ltd., Madhya Pradesh	100	Electricity for running paper industry	Ipomia wood
2.	Senapathy Whiteley Pvt. Ltd., Ramanagaram, Karnataka	500	Electricity for varying load in industrial applications	Mulberry stalk and coconut shells

Source: [79].

projects aimed at linking producer gas to steam turbines could not proceed beyond gasifier design. The concept of bagasse gasification also did not show much potential for commercial implementation.

The only viable technologies for commercialization of electricity production from biomass are: (1) biomass gasification coupled with an IC engine operating on producer gas, and (2) boiler-steam turbine route (or cogeneration). The technology of biomass gasification is suitable for distributed and decentralized generation in remote villages. A single biomass gasification unit (with either updraft or downdraft design) can generate up to 500 kW power, while a gasification station (with fluidized bed design) could have capacity of about 5 MW. Typically, the costs of biomass gasifier-based electricity generation ranges from Rs. 4 to 4.5 crore/MW_e (Rs. 40–45 million/MW_e). Active and intense research in this area is going on all around the world in terms of better design and optimization of process parameters, which is aimed at improving energy efficiency of the gasifier that would bring down the cost of electricity generation in the near future.

Bagasse-based cogeneration has already been adopted by many sugar mills. In this route, high pressure steam is first utilized for generation of electricity and later for meeting the heat requirements of the process. Thus, the overall efficiency of fuel utilization is quite high, in the range of 60%. Typically, the cost of electricity produced through this route is somewhat cheaper than biomass gasification route; in the range of Rs. 3–4 crore/MW_e (Rs. 30–40 million/MW_e). Revenues earned from electricity cogeneration have improved economy of sugar mills. However, cogeneration units are preferred only for capacities > 5 MW, and these units could be installed and implemented in an industrial area. Thus, they are not suitable for applications in remote rural areas where grid connectivity is not possible. Secondly, the steam turbine-based technology has already reached maturity. Any path-breaking efficiency improvement is, thus, not feasible. Thus, in terms of technology development and breakthrough for large capacity systems, gasification combined with IC engines may turn out a better option.

3.4. Biomass gasification efforts in India

The biomass gasification program in India started mainly as a R&D effort with joint efforts of MNES, various academic institutions and private entrepreneurs [22,23]. These efforts were initiated in the mid-1980s for development and subsequent commercialization of an efficient and economically viable technology for decentralized electricity generation from biomass, especially in remote and rural areas. The MNES set up five Gasifier Action Research Projects at I.I.T. Bombay, I.I.T. Delhi, I.I.Sc. Bangalore, M.K. University Madurai and SPRERI, V.V. Nagar. Research in these centers contributed immensely towards technology development, prototype fabrication and transfer of technology to commercial manufacturers. Combustion, Gasification and Propulsion Laboratory (CGPL) at I.I.Sc. Bangalore developed downdraft, atmospheric gasification technology for up to 500 kW systems along with effective gas cleaning systems. These gasifiers have been put to use for large-scale power generation. Several commercial manufacturers have obtained license from I.I.Sc. Bangalore for manufacture of downdraft gasifiers based on I.I.Sc. technology. Some of these manufacturers are M/s Bioresidue Energy Technology Pvt. Ltd., M/s Energreen Power Ltd., M/s Arrya Hi-Tech Energy and M/s NetPro Renewable Energy (India) Pvt. Ltd. More than 25 gasifiers based on I.I.Sc. Technology have been installed in India and abroad for diverse applications such as thermal, village electrification, water pumping applications, industrial applications (captive electricity generation) and research and educational purpose. Table 9A lists some of the gasifier installations based on I.I.Sc. Technology in India and abroad. SPRERI (V.V. Nagar, Gujarat) has also developed gasifiers for different energy requirements. These gasifiers are adopted for groundnut shells and installed in the ceramic industries for baking of raw items at about 900–1300 °C. Due to these installations, the oil consumption of the industry has reduced by almost 70%. M.K. University at Madurai has also made vital contributions to development of gasifiers suitable for industrial applications. The major achievement of this center is in terms of adoption of the gasifiers for high temperature applications typical of ceramic and aluminum industries.

Noteworthy R&D efforts of technology development have also taken place in industrial sector. Among the companies that have indigenously developed biomass gasification technologies in the country, remarkable contribution has been made by M/s Ankur Scientific Technologies Ltd. in Vadodara, Gujarat. This company has manufactured atmospheric downdraft gasifiers with wide range capacities – 5 to 500 kW. Various installations of Ankur Gasifiers have been listed in Table 9B. To summarize, the biomass gasifier-based thermal and electricity generation has tremendous growth potential in the country. MNRE has offered attractive financial support in terms of capital subsidies (Rs. 125,000 per 300 kW_{th} for thermal application and Rs. 150,000 per 100 kW_e for electrical applications in 2006) for gasifier installations in India. Table 10 gives information on state-wise gasifier installation (as of 31 March 2003).

Table 9B
List (partial) of installation of gasifiers for various applications (based on Ankur Scientific Technology).[a]

S. No.	Location	Capacity (kWe)	Function	Biomass employed
Captive power generation				
1.	M/s Sree Gopal Rice Hills, West Bengal	120 (dual fuel)	Generation of power for meeting energy needs of the mill, reduction in diesel consumption	Rice husk
2.	M/s Sree Brijuka Agro Products Pvt. Ltd.	350 (dual fuel)		
3.	M/s Valli Chlorate, Kolvilpatti	200 (100% producer gas)		
4.	M/s Meghaplast	250 (100% producer gas)		
Village electrification				
1.	Gosaba Islands, Sundarban	100 (5 units)	Domestic and street lighting, drinking water, grinding machines, water irrigation	Pieces from different species of agro-residues
2.	Gasifier power plant, Kumarikanan, Purulia	50 (2 units)		
Industrial applications				
1.	M/s Mahabhadra Industrial Gases Co.	150	Clean CO_2 generation (sulfur free)	Woody biomass
2.	M/s Patson Industries Ltd.	60	Annealing of steel tubes	Woody biomass

[a] M/s AnkurScientific has installed more than 700 gasifiers worldwide using different kinds of biomasses as feedstock. More detailed information on these installations could be obtained from website of the company. *Source*: [80].

4. Technology for biomass gasification

Before we proceed to analysis of technical and economic feasibility of decentralized power generation through biomass gasification in the Indian context, we would like to discuss various technologies available for gasification of biomass and present a comparative analysis of the same. Depending on the mode of biomass–air (or oxygen) contact, biomass gasifiers are classified into two main types, viz. (i) fixed bed, and (ii) fluidized bed. The sub-categories for the fixed bed type gasifiers based on the relative directions of biomass and air flow are (a) updraft, (b) downdraft, and (c) cross-draft gasifiers. The sub-categories for the fluidized bed gasifiers based on the mode of fluidization are (a) bubbling bed and (b) circulating fluidized bed gasifiers. In addition to these, entrained bed gasifiers (as for coal gasification) were also developed for biomass, but they proved unsuitable for biomass material as biomass could not easily ground to the particle size range (100–400 μm) as required for these gasifiers. Pre-treatment of biomass and properties of biomass also influence the performance of gasifiers. In addition, proper cleaning and conditioning of gas is of utmost importance for proper functioning of the generator sets, in terms of both stability and efficiency. In this section we shall briefly touch upon these technical aspects. We begin with the basic chemistry involved in biomass gasification.

Table 10
State-wise biomass gasifier installations (as of 31.03.2003).

State	Installed capacity	
	No. of units	Net generation (kW)
Andhra Pradesh	231	15,384
Arunachal Pradesh	3	180
Assam	6	123
Bihar	2	20
Chhattisgarh	1	500
Goa	3	22
Gujarat	237	11,961
Haryana	25	964
Himachal Pradesh	2	7
Jammu and Kashmir	4	120
Karnataka	476	4499
Kerala	13	725
Madhya Pradesh	144	4529
Maharashtra	316	3823
Mizoram	2	200
Orissa	16	72
Punjab	27	700
Rajasthan	21	218
Tamil Nadu	83	2652
Tripura	4	1000
Uttar Pradesh	50	2746
West Bengal	27	4100
Andaman and Nicobar Islands	17	167
Delhi	16	74
Others	91	318
Total	1817	55,104

Source: [81].

4.1. Chemistry of biomass gasification

The chemistry of biomass gasification is quite complex. However, on a broad basis, the following stages are involved in the gasification process [24–27]:

- *Drying*. In this stage, the moisture content of the biomass is reduced. Typically, the moisture content of biomass is in the range 5–35%. Drying occurs at about 100–200 °C with reduction in moisture content of biomass to <5%.
- *Devolatilization (or pyrolysis)*. This is essentially thermal decomposition of biomass in absence of oxygen or air. As the name suggests, in this process the volatile matter in the biomass is reduced. This results in release of hydrocarbon gases from biomass due to which the biomass is reduced to solid charcoal. The hydrocarbon gases can condense at sufficiently low temperature to generate liquid tars.
- *Oxidation*. This is reaction between solid carbonized biomass and oxygen in the air resulting in formation of CO_2. Hydrogen present in the biomass is also oxidized to generate water. Large amount of heat is released with the oxidation of carbon and hydrogen. If oxygen is present in substoichiometric quantities, partial oxidation of carbon may occur resulting in generation of carbon monoxide.
- *Reduction*. In absence (or substoichiometric presence) of oxygen, several reduction reactions occur in the temperature range 800–1000 °C. These reactions are mostly endothermic. The major reactions in this category are as follows:

$$\text{Water-gas reaction}: \quad C + H_2O \rightarrow CO + H_2 - 131.4\,\text{kJ/gmol}$$

$$\text{Bounded reaction}: \quad C + CO_2 \rightleftarrows 2CO - 172.6\,\text{kJ/gmol}$$

$$\text{Shift reaction}: \quad CO_2 + H_2 \rightleftarrows CO + H_2O - 42\,\text{kJ/gmol}$$

$$\text{Methane reaction}: \quad C + 2H_2 \rightleftarrows CH_4 + 75\,\text{kJ/gmol}$$

A comprehensive description of different zones in the gasifiers, their temperature ranges and the reactions occurring in these zones is given in Table 11. Depending on directions of air and

Table 11
Various zones in the gasifiers and the reactions occurring therein.

S. No.	Zone	Temperature range (°C)	Reactions
1.	Drying zone	30–65	H_2O(moisture) $\rightarrow$ H_2O(steam)
2.	Preheating zone	100–200	–
3.	Devolatilization (or pyrolysis) zone	200–600	$C_xH_yO_z \rightarrow$ volatile gases and tar
4.	Oxidation zone	1000–1200	$C + 0.5O_2 \rightarrow CO + 268$ kJ/gmol $C + O_2 \rightarrow CO_2 + 406$ kJ/gmol $H_2 + 0.5O_2 \rightarrow H_2O + 242$ kJ/gmol
5.	Reduction zone (primary)	800–1000	$C + H_2O \rightarrow CO + H_2 - 131.4$ kJ/gmol $C + 2H_2O \rightarrow CO_2 + 2H_2 - 78.7$ kJ/gmol $C + CO_2 \rightleftarrows 2CO - 172.6$ kJ/gmol $CO + H_2O \rightleftarrows CO_2 + H_2 + 42$ kJ/gmol $CO + 3H_2O \rightleftarrows CH_4 + H_2O + 88$ kJ/gmol
6.	Reduction zone (secondary)	800–1000	$C + CO_2 \rightleftarrows 2CO - 172.6$ kJ/gmol $CO_2 + H_2 \rightarrow CO + H_2O - 41.2$ kJ/gmol $C + 2H_2 \rightarrow CH_4 + 75$ kJ/gmol
7.	Ash collection pit	<500	–

biomass flow, the sequence of these zones in the gasifier varies. The extent of these reactions depends on two major factors, viz. temperature and equivalence ratio (ER), defined as:

$$\mathrm{ER} = \frac{(\text{weight of oxygen/weight of dry fuel})_{\text{actual}}}{(\text{weight of oxygen/weight of dry fuel})_{\text{stoichiometric}}}$$

The denominator of the above expression is the amount of oxygen required for complete combustion of the fuel. This quantity depends on the composition of the fuel, i.e. C, H, N, O content of the fuel. The most important components of the producer gas resulting from biomass gasification are CO and H_2. Typically, an ER of 0.2–0.4 is considered to be optimum for gasification process. For ER < 0.2, pyrolysis dominates that results in generation of tars, while for ER > 0.4, combustion reactions dominate resulting in generation of CO_2.

Temperature is a critically important parameter in the gasification process. For high carbon conversion, temperature of 800 °C or above is essential. The fraction of carbon monoxide in the producer gas increases with temperature. In addition, high temperature also helps in cracking of tar, which results in reduction in aromatic content of the tar. In addition, temperature also influences formation of nitrogen compounds such as ammonia and HCN.

4.2. Biomass pre-treatment and properties

Pre-treatment. The pre-treatment biomass comprises mainly of two steps: (1) drying and (2) particle size reduction. Typical moisture content of the fresh wood is 50–60% (w/w). The desired moisture content of biomass for gasification purpose is in the range of 10–15% (w/w). The appropriate particle size of biomass for gasification depends on the design of gasifier. For fixed bed gasifier, particle size range is 20–80 mm, while for fluidized bed gasifier it is still lower – in the range of ~1 mm or smaller. Two additional treatments that can be applied to biomass are fractionation and leaching. These are aimed at reducing the nitrogen and alkali content of biomass so as to limit the impurities in the producer gas obtained from gasification.

Influence of biomass properties. Moisture content of the biomass is a parameter of critical importance. As noted earlier, appropriate moisture content of biomass is in the range 10–15%. Moisture content higher than 30% can make the ignition of the gasifier difficult and also reduces the calorific value of the producer gas [24]. Significant heat is required to evaporate the moisture prior to gasification or combustion. Higher moisture content also reduces the temperature of the combustion zone of the gasifier that has leads to incomplete cracking of hydrocarbons or tars released from pyrolysis zone. In addition, the extent of water gas shift reaction increases that result in production of more H_2. Thus, direct hydrogenation of carbon in biomass can occur resulting in production of methane. Consequently, the production of carbon monoxide reduces. As the combined heat of combustion of H_2 and CH_4 is lesser than the heat of combustion of CO, the net calorific value of the producer gas decreases.

4.3. Fixed bed gasification

Updraft gasifiers. A schematic of the updraft gasifier is shown in Fig. 4. In these gasifiers, the feed is introduced from the top and air is introduced from the bottom through grate. Feed and air move countercurrently in the gasifier. The lowest portion of the gasifier is essentially the "combustion" zone where the char formed due to drying and devolatilization of biomass is combusted. This helps in raising the temperature of the lower portion of the gasifier to about 1000 K. Hot gases passing upward through the bed of downflowing biomass are reduced in the portion immediately above the combustion zone. Further up the gasifier, the hot gases pyrolyse the biomass and dry it. These processes cool the gases to about 200–300 °C. Pyrolysis of biomass results in release of volatiles and formation of sizeable amount of tar. Some of this tar may leave with the outgoing gases. The overall efficiency of the process could be high due to low temperature of the gases leaving the gasifier. In addition, the gas flowing through the packed bed of biomass undergoes "filtration" as the particulate matter entrained with it is captured by the bed material. This helps in lowering of the particulate content of the outgoing gas. The humidity of the gasifying air plays a major role in controlling the temperature of the gasification [25,28,29].

Downdraft gasifier. The downdraft design is essentially same as the updraft design except that both feed and air move concurrently from top to bottom of the gasifier. Fig. 5 shows a schematic of the downdraft gasifier. Since the exit of the producer gas is close to the combustion zone of the gasifier with maximum temperature, the tar formed during devolatilization of biomass is thermally cracked to some extent. Thus, the tar content of the producer gas from downdraft design is lower than that in the updraft design. However, disadvantage of this type of design is that the gases leave at much higher temperature and amount to significant heat loss from the gasifier, thus lowering its thermal efficiency. In addition the particulate content of the gas is also high. Despite these demerits, downdraft design enjoys greater popularity due to

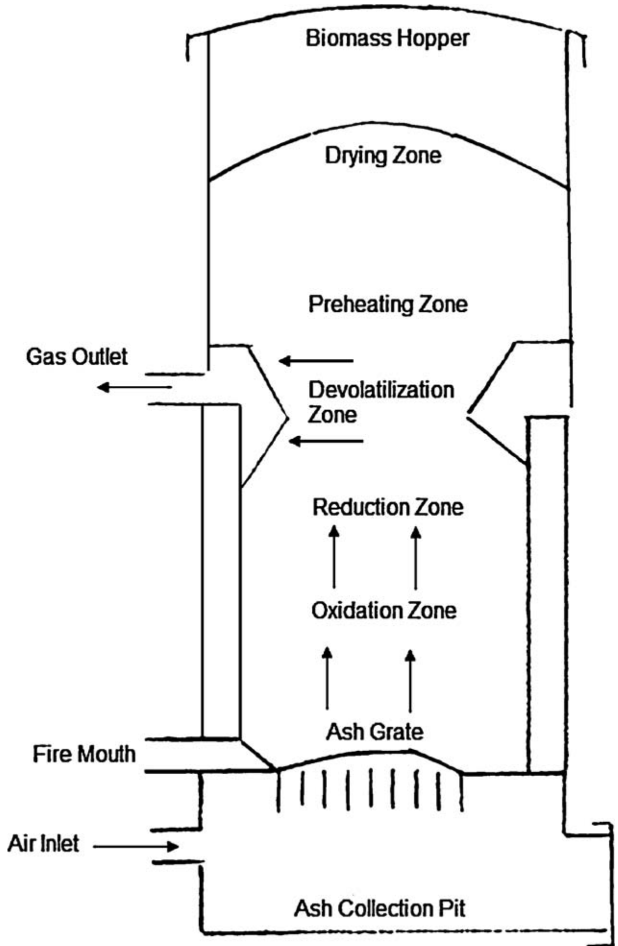

Fig. 4. Schematic of an updraft biomass gasifier (adopted from [27]).

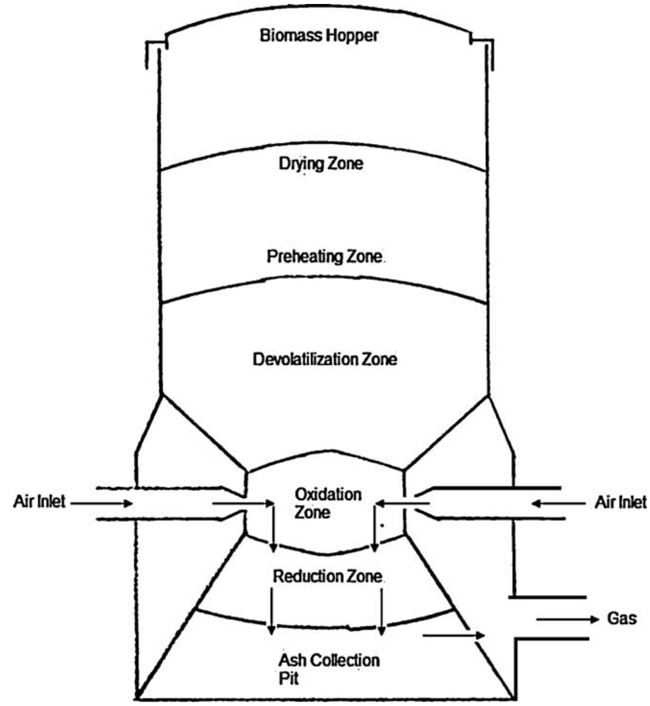

Fig. 5. Schematic of a downdraft gasifier (adopted from [27]).

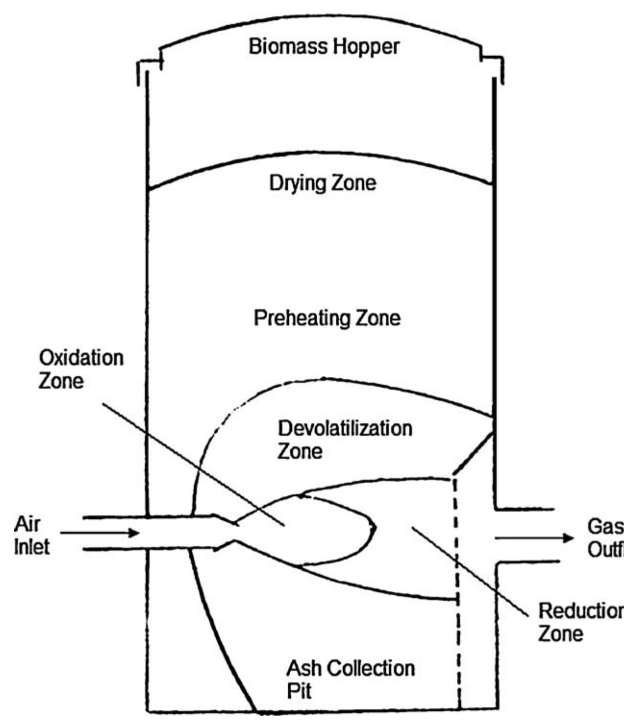

Fig. 6. Schematic of a cross-draft biomass gasifier (adopted from [27]).

its low tar content gas. Tar in the producer gas can condense over the shaft of the engine causing operational problems causing frequent shutdowns and cleanup. Thus, low tar content gas is always preferred for firing the gas engines and turbines.

Cross-draft gasifier. In this design, the biomass feed is introduced from top and the air from the side of the gasifier. The biomass moves down as it gets dried, devolatilized, pyrolysed and finally gasified, while the air exits from opposite side of the unit. The exit for the gas is more-or-less at the same level as that of entrance. The combustion and gasification zone is located near the entrance of the air while the devolatilization and pyrolysis zones are at a higher level than the entrance and exit. Fig. 6 shows a schematic of the cross-draft gasifier. The producer gas leaves the gasifier at almost same temperature as gasification (~800–900 °C). Thus, the heat loss from gasifier is high that reduces its thermal efficiency. Secondly, the overall residence time of the producer gas in the high temperature zone is small (as the gas enters and exits from opposite ends), and hence, tar cracking is limited. This leaves significant amount of tar in the outgoing gas.

Overview of fixed bed biomass gasification. Typical composition of the producer gas from fixed bed gasifiers is: 40–50% N_2, 15–20% H_2, 10–15% CO, 10–15% CO_2 and 3–5% CH_4 [25,26,30–32]. Thus, the net calorific value of the gas is in the range 4–6 MJ/N m^3. Nitrogen in the producer gas contributes considerably to the volume of the producer gas, which increases the size of the downstream equipment. The moisture content of the biomass is another parameter of paramount importance. Typically, the moisture content of biomass should be in the range 10–15%. Thus, considerable predrying of biomass is necessary. Many commercial fixed bed downdraft gasifiers have the facility of using waste heat from engine exhaust for predrying of the biomass. Typically, about three-fourth of the energy content of the biomass appears in the producer gas with radiation heat losses, sensible heat of producer gas and heat content of ashes accounting for the rest one-fourth of energy. The principal products of the devolatilization process are volatiles and char. Volatiles exit with outgoing gas, while the char undergoes combustion. This char can be gasified further to improve the gas yield from the process. Typical yield of char varies from 20 to 40% (w/w) of dry biomass. However, reactivity of

the char is a matter of question. The reactivity varies significantly with the composition of the char, especially the carbon and nitrogen content. McKendry [25] has proposed a two-stage gasification process, in which pyrolysis of the biomass occurs in the first stage at about 600 °C using external heat. The gases from this stage may contain considerable amount of tar, which is cracked either catalytically or by reaction with steam. The second stage comprises of gasification of the char produced from first stage using the gases from first stage after tar removal.

4.4. Fluidized bed gasification

Fluidized bed processes [25,26] were first commercialized for coal gasification [33]. The first commercial fluidized bed process, Winkler gasifier, went into operation in Germany in 1941. Thereafter, fluidized bed processes have been extensively implemented by the petroleum refineries and petrochemical industries. In recent years, fluidized bed biomass gasification is becoming increasingly popular. The distinct merits of these processes over fixed bed biomass gasifiers are uniform temperature distribution in the reactor due to excellent gas–solid mixing, high carbon conversion with low tar production and flexibility in terms of fuel type, feed rate, particle size and moisture content. Typical capacity of the fixed bed gasifiers is 50–500 kW. However, due to above-mentioned features, scale-up and operation of the fluidized bed gasifiers for electricity generation in MW scale is much easier. There are two main types of fluidized bed gasification systems, viz. bubbling fluidized bed and circulating fluidized bed. Depending on scale of operation, the cyclone separators for capture and recycle of solid particles could be placed either internally or externally. It must be mentioned that internally circulating fluidized bed reactors combine the design features possess of both bubbling and fluidized mode and thus have characteristics of both modes. In the past two decades significant experimental and theoretical research has taken place in design, development and scale-up of fluidized bed gasifiers [34–43]. We describe below the design and operational features of these two kinds of fluidized systems.

Bubbling bed systems (BFB). In these kind of systems, the bed material (which could be mixture of inert particles such as sand along with finely ground biomass) rests on a distributor plate (either perforated or porous type) through which the fluidizing medium, i.e. air is passed at velocity about five times that of minimum fluidization velocity. Typical temperature in the bed is about 700–900 °C. The feed, which is finely grained biomass, is introduced just above the distributor plate. The biomass first undergoes pyrolysis in the hot bed above distributor to form char and gaseous products due to devolatilization. The char particles are lifted along with fluidizing air and undergo gasification in relatively upper portions of the bed. Due to contact with high temperature bed, the high molecular weight tar compounds formed are cracked; thus reducing the net tar content of the producer gas to less than 1–3 g/N m^3.

Circulating fluidized beds. Circulating fluidized beds (CFB) is an extension of the concept of bubbling bed fluidization. In this case the velocity of the fluidizing air is much higher than the terminal settling velocity of the bed material. Thus, the entire bed material (biomass + inert material such as sand) is lifted by the fluidizing air. The exhaust of the gasifier is a relatively lean mixture of solids and gas. This exhaust is admitted into a cyclone separator where solids get disengaged from the gas and are returned to the bed through a downcomer pipe. Depending upon the solids concentration and size distribution either single stage or multi-stage cyclones are employed. Circulation of the biomass particles is carried out till the particles are reduced in size due to combustion/gasification. An advantage that circulating fluidized bed design offers is that gasifier can be operated at elevated pressures.

The summary of the salient features and comparative evaluation of fixed and fluidized bed type biomass gasifiers is presented in Table 12.

4.5. Post-treatment of producer gas

The producer gas obtained from fixed and fluidized bed gasifiers contains many impurities, with ash and tar being the main impurities. The cyclone separator are usually unable to remove particulate impurities below 10 μm. Removal of finer particles can be achieved using filter bags, sintered ceramic candles or metallic candles. However, depending on the operational load these devices may clog due to soot and/or tar adhering to ash particles. Wet scrubbing of gas is a common technique used for removal of particulate matter. Various wet scrubbing techniques include spray towers, centrifugal spray towers, packed bed column scrubbers, ejector venture scrubbers and free jet washers [27].

Effective removal of tar has been a principal problem in producer gas cleaning. Tar mainly comprises of condensable aromatics and polyaromatics. If the gas is to be used in engines or turbines, the tar removal is utmost essential as the condensation of tar on mechanical components moving with high speed can cause mechanical instability. The principal tar components are toluene, naphthalene and phenol with many other aromatics comprising of up to seven benzene rings as secondary components [27]. Over past several decades extensive research has taken place on removal of tar from producer gas (for state-of-the-art review on tar elimination techniques has been given by Devi et al. [44]). The primary methods of tar removal includes (1) optimization of gasifier operating conditions in terms of air ratio, bed temperature and sufficient residence time; (2) use of bed additives or catalysts (such as nickel-based catalysts, calcined dolomites, magnesites, zeolites, olivine and iron catalysts) that act as tar reducers; (3) modification of gasifier design, i.e. splitting the gasifier into two stages – pyrolysis stage and reduction stage. The secondary methods of tar removal consist of physical or chemical treatment such as (1) either thermal or catalytic cracking of tar downstream of the gasifier and (2) mechanical removal of tar using cyclone separator and baffle/ceramic/fabric/electrostatic filter. Some times a multi-stage process is used for secondary gas cleaning [45]. Although very effective in tar removal, the secondary methods have not been economically viable [46,47]. If the application of the producer gas is for purpose of direct combustion, tar removal prior to combustion is not necessary. If the burner is designed properly, all of the tar gets burnt.

5. Economics of biomass gasification

The principal components of the capital cost of biomass gasifier system (either updraft or downdraft) are biomass gasifier unit (which is essentially a combustion–gasification chamber made of stainless steel), a gas cooling and cleaning unit (comprising of scrubber and two or three stage filters for removal of particulate matter) and an engine-generator (which could be either of dual fuel type, employing diesel as pilot fuel or it could be operating on 100% producer gas). Other components of capital cost of gasifier system include civil construction (room shed and concrete supports various components of gasifier systems), biomass preparation and storage units, electrical wiring and piping, tar removal/cracking system, ash removal facility and distribution network for dissemination electricity to local consumers. The operating costs of the gasifier system include oil or fuel, i.e. biomass (including its preparation) and diesel (for duel fuel engine), labor charges, maintenance charges and replacement of spare parts on occasional basis.

The composition of the producer gas shows variation with gasifier type and design, fuel to air ratio, biomass type, etc. Typical

Table 12
Salient features and comparative evaluation of different designs of biomass gasifiers.

Gasifier type	Salient features	Gasifier type	Salient features
Downdraft	Simple and proven technology Fuel specificity in terms of both type and size Suitable for biomasses with low moisture Producer gas with moderate calorific value and low tar and ash (or particulates) content High exit gas temperature Suitable for capacity of 20–200 kW High residence time of solids High overall carbon conversion Limited scale-up potential with maximum capacity of 250 kW	Bubbling fluidized bed	High fuel flexibility in terms of both size and type Flexibility of operation at lower loads than design load Ease of operation Low feedstock inventory Good temperature control and high reaction rates Good gas–solid contact and mixing In-bed catalytic processing possible Producer gas with moderate HHV but low tar levels and high particulates Carbon loss with ash High conversion efficiency Suitable for large-scale capacities (up to 1 MW or even higher) Good scale-up potential
Updraft	Simple and proven technology Low exit gas temperature High thermal efficiency Producer gas with moderate calorific value but high tar and ash (or particulates) content High residence time of solids High overall carbon conversion Necessity of extensive gas cleanup before use in engines Suitable for capacities up to 250 kW Limited scale-up potential	Circulating fluidized bed	High fuel flexibility in terms of both size and type Flexibility of operation at lower loads than design load Ease of operation Low feedstock inventory Good temperature control and high reaction rates In-bed catalytic processing possible Producer gas with moderate tar levels but high particulates High carbon conversion Good gas-slid contact and mixing Suitable for large-scale capacities (up to 1 MW or even higher) High conversion efficiency Very good scale-up potential
Entrained flow bed	Relatively complex construction and operation Fuel specificity in terms of particle size (costly feed preparation) Low feedstock inventory High temperature give good gas quality Materials of construction problems with high temperature Good gas–solid contact and mixing Producer gas with moderate HHV and low tar content High conversion efficiency Suitable for high capacities (>1 MW) Very good scale-up potential	Twin fluidized bed	Relatively complex construction and operation Producer gas with moderate HHV and moderate tar levels Cleaning of gas before firing into engines required In-bed catalytic conversions possible Good gas–solid contact and mixing Relatively low efficiency Suitable for high specific capacities (>1 MW) Good scale-up potential but relatively complex design

Source: [25,27,29,61].

composition of producer gas was described in Section 4.3. In a duel fuel engine generator, the producer gas can replace up to 80% of diesel. Most of the gasifiers fabricated prior to 2002–2003 employed a dual fuel engine. However, more recently 100% produced gas engines have appeared in market. As of 2004 end, more than 1800 gasifiers have been installed in India, amounting to more than 75 MW generating capacity. Ministry of New and Renewable Energy promotes the decentralized electricity generation by offering capital subsidy up to 90% for package of 50 kW project covering civil construction and local distribution network [9].

Analysis of the economics of the gasifier system has been done by several authors. We present herewith an overview of the same. The "measures" of the economic feasibility of the biomass gasifier for decentralized power generation are: (1) the levelized unit cost of electricity (LUCE) produced by the gasifier in comparison to diesel generator and (2) the breakeven analysis (i.e. comparison of the diesel price, for which gasifier is feasible with the prevalent market price of diesel). We first present the economic analysis of low- to medium-scale gasifiers (5–100 kW) with the two approaches mentioned above. This is followed by analysis of medium- to large-scale system (0.5–5 MW). We begin with discussion on cost facts involved in economic analysis.

5.1. Factors affecting cost of power generation

As noted earlier, the principal capital cost of biomass power projects includes cost of gasifier, engine generator, civil construction, biomass preparation unit, electricity distribution network and electrical and piping connections to the site of gasifier installation. In addition to this, several other factors influence the cost of power generation. These are: (1) specific fuel consumption (at full and part loads), (2) capacity utilization factors, (3) useful life of gasifier and generator, and lastly, (4) the unit price of biomass and supplementary fuel, i.e. diesel (in case of duel fuel system). The comprehensive list of factors and their typical values in the Indian context are given in Table 13. This data is adopted from work of Nouni et al. [48]. The contribution of various components to the total capital cost of the gasifier of different capacities and employing duel fuel or 100% producer gas engine is described in Fig. 7. The economy of scale (i.e. total capital cost per kW of installed capacity or unit capital cost) also shows an interesting variation with duel fuel or 100% producer gas engine, as depicted in Fig. 8. Unit capital cost shows a sharp reduction with capacity for a dual fuel engine, while for gasifiers employing 100% producer gas capital cost reduces only marginally with capacity rising from 5 to 40 kW. We would like to

Table 13
List of parameters (along with their typical values) for economic model of low- to medium-scale biomass gasifiers.

Parameter	Value
1. Maintenance costs of gasifier system components (as a fraction of their capital costs)	
a. Gasifier	0.05
b. Engine-generator set	0.10
c. Electricity distribution network	0.03
d. Civil works related to gasifier installation	0.02
e. Auxiliary power consumption	0.10
2. Capacity utilization factor	25%
3. Discount rate (for annualization of capital costs)	10%
4. Manpower	Rs. 15 per person per hour
5. Manpower requirement	1 no. for $\leq$20 kW system 2 nos. for >20 kW system
6. Fuel costs	
a. Biomass (main fuel)	Rs. 1.5 per kg
b. Diesel (pilot fuel)	Rs. 30.45 per liter
7. Sales tax	4%
8. Specific consumption of biomass (main fuel) in dual fuel engine	
a. At 100% rated capacity	1.1 kg kWh^{-1}
b. At 75% rated capacity	1.21 kg kWh^{-1}
c. At 50% rated capacity	1.32 kg kWh^{-1}
9. Specific consumption of diesel (pilot fuel) in dual fuel engine	
a. At 100% rated capacity	0.11 L kWh^{-1}
b. At 75% rated capacity	0.10 L kWh^{-1}
c. At 50% rated capacity	0.11 L kWh^{-1}
10. Specific consumption of biomass (main fuel) in 100% producer gas engine	
a. At 100% rated capacity	1.4 kg kWh^{-1}
b. At 75% rated capacity	1.54 kg kWh^{-1}
c. At 50% rated capacity	1.68 kg kWh^{-1}
11. Specific consumption of diesel in diesel generator engine	
a. At 100% rated capacity	0.30 L kWh^{-1}
b. At 75% rated capacity	0.28 L kWh^{-1}
c. At 50% rated capacity	0.30 L kWh^{-1}
12. Unit cost of electricity distribution network	Rs. 1,25,000 km^{-1}
13. Useful life period of components	
a. Engine generator set (with diesel as main or pilot fuel)	20,000 h
b. Biomass gasifier	10,000 h
c. Electricity distribution network	20 years
d. Civil works	20 years

Source: [48].

specifically mention that other groups have also done the economic analysis for similar size of gasifiers [4,22,49–53], however, using a different approach.

5.2. Feasibility of low- to medium-scale units (5–100 kW systems)

As noted earlier, there are two approaches, viz. LUCE and breakeven price of diesel for assessment of the economic feasibility of low- to medium-scale gasifiers. We present below description of these approaches and the results on economic viability of gasifier-based power generation using these approaches:

- *LUCE approach*. Kandpal and co-workers [9,18,48,54–56] have proposed the method of LUCE for assessment of economic feasibility of low- to medium-scale power projects with renewable energy. This method is applied for biomass gasifier-based power projects as follows:
  1. The net electricity produced from the project with installed capacity P in a year (365 days of operation with 24 h production) is determined as follows: $E_O = 8760P$. Out of this production, a fraction is utilized for meeting the energy needs of the plants itself and some power is lost through transmission and distribution. Moreover, the capital utilization factor is also an important factor. With this taken into account, the net production is
  $$E_O = 8760 \cdot (1-a) \cdot (1-l) \cdot CUF$$
  2. The total capital cost for the project comprises of four components viz. gasifier, engine-generator, civil works and distribution network. This cost is annualized using capital recovery factor as follows: $AC_c = C_gR_g + C_{eg}R_{eg} + C_{cw}R_{cw} + C_{dn}R_{dn}$; where $R = (d(1+d)^T)/((1+d)^T - 1)$ is the capital recovery factor for discount rate d and life period of T years. Various notations are as follows: C_g, C_{eg}, C_{cw} and C_{dn} are capital costs of gasifier, engine-generator unit and civil works related to gasifier installation and electricity distribution network, respectively.
  3. The operating and maintenance cost is expressed as fraction of the capital cost as follows:
  $$AC_{O\&M} = C_gm_g + C_{eg}m_{eg} + C_{cw}m_{cw} + C_{dn}m_{dn} + 8760 \cdot CUF \cdot m_l \cdot n$$
  where m is the fraction of the total capital cost taken for maintenance and operation of the gasifier unit (with subscript denoting the fraction corresponding to the component). m_l and n are the wage rate of manpower and nos. of labor required for operation of the gasifier.
  4. The cost of fuel consumption is: $AC_F = 8760CUF(C_{pf}S_{spfc}P + C_{bm}S_{sbmc}P)$. *Notation*: C_{pf} is the unit cost of pilot fuel (diesel), C_{bm} is the unit cost of biomass fuel, while S_{spfc} and S_{sbmc} are the specific fuel consumption of pilot fuel and biomass per kWh of electricity generated.
  5. The unit cost of electricity after substitution of all annualized costs is determined as:
  $$LUCE = \frac{AC_C + AC_{O\&M} + AC_F}{E_O}$$
  6. If a part of the capital cost (fraction x) is available to the investors on soft loan (with interest rate d_1), then the expression for LUCE is modified by multiplication of the soft loan fraction of all capital costs components and the operations and maintenance costs for these components with modified capital recovery factor calculated using interest rate d_1 as: $R_1 = (d_1(1+d_1)^T)/((1+d_1)^T - 1)$. The cost for manpower and fuel consumption, however, stays the same.

The overall variation in LUCE for biomass gasification projects with 5–40 kW rated capacity in comparison to diesel generator sets is shown in Fig. 9. Also shown in Fig. 9 is the influence of plant load factor and soft loan on the capital cost. Using above methodology, the following trends have been observed in the economic feasibility of biomass gasification-based power generation:
1. Biomass gasification-based electricity generation using duel fuel engine is found competitive with diesel generators only for capacities higher than 20 kW. However, 100% producer gas engines are not economically attractive even for 40 kW capacities.
2. The plant load factor is a crucially important parameter. Biomass gasification with duel fuel engine is economically unfeasible for even 75% load in comparison to diesel generators.
3. If electricity distribution network already exits at the installation site, it reduces the LUCE by 20%, making biomass gasification even more attractive.

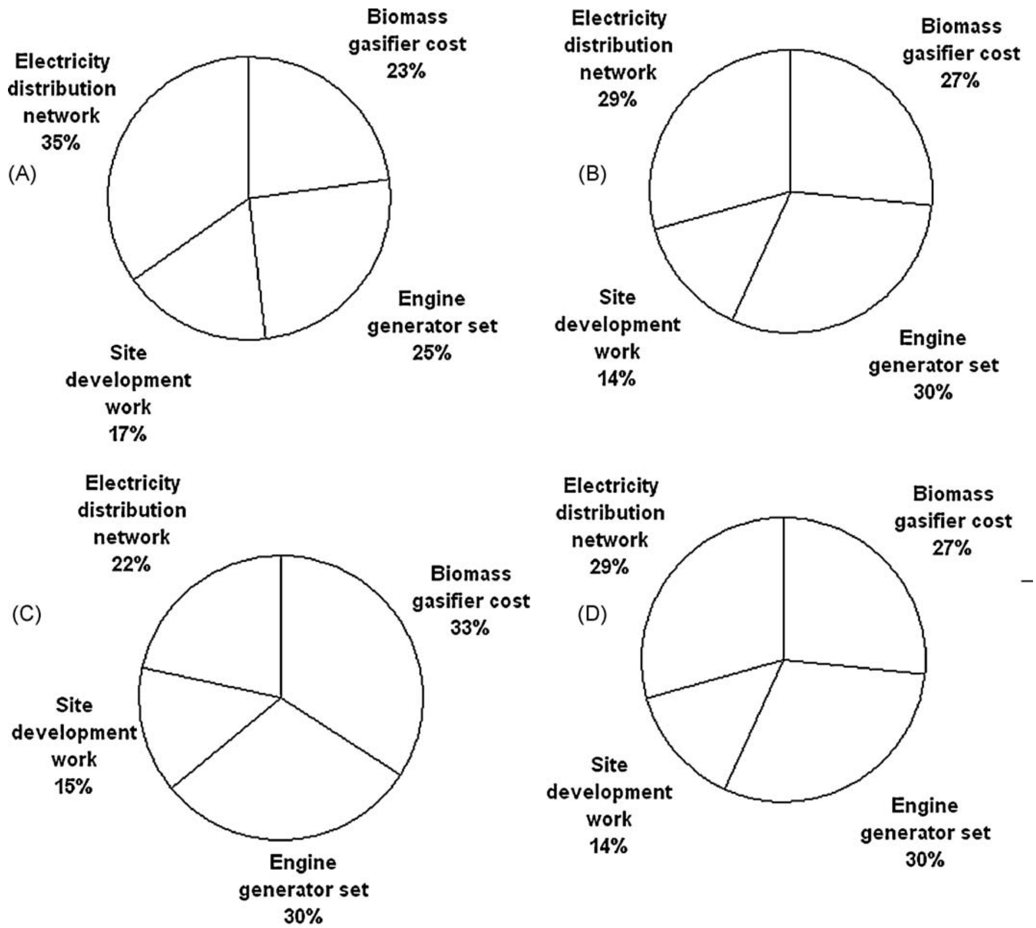

Fig. 7. Capital cost distribution of biomass gasifier power projects. (A) 10 kW gasifier employing dual fuel generator. (B) 40 kW gasifier employing dual fuel generator. (C) 9 kW gasifier employing 100% producer gas generator. (D) 40 kW gasifier employing 100% producer gas generator.

4. Splitting of gasifier capacities (in view of smaller day time loads and larger night time loads) helps in reduction of capital cost but not LUCE.
5. Capacity utilization factor is also a crucially important factor influencing the economy of power generation. Higher capacity utilization factor add to economy of biomass gasification.

Similar conclusions about biomass gasification-based power generation have been drawn by other authors [22,50,52,57–59].

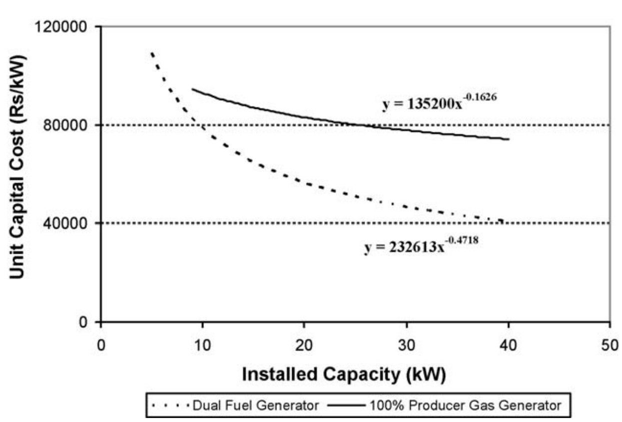

Fig. 8. Economy of scale (variation of unit capital cost per installed capacity, in Rs/kW, with total installed capacity) for biomass gasifier power projects using either dual fuel generator or 100% producer gas generator.

- *Breakeven price approach*. Breakeven price of the pilot fuel used in dual fuel generator sets could be used as a measure of the financial viability of biomass gasifier. However, the results of this approach depend on the definition of the breakeven price used. We give below summary of the work of Siemons [53] and Nouni et al. [48] who have used this approach with different definitions of the breakeven price.

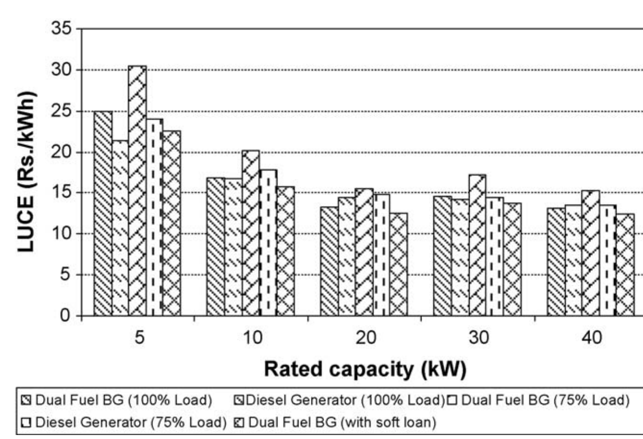

Fig. 9. Variation in levelized unit cost of electricity (LUCE) with different factors (type of generator, plant load factor, soft loan availability). The LUCE for the diesel generator with 75% plant load factor is shown as base case for comparison.

The formula used by Siemons [53] for calculation of the breakeven price of diesel is:

$$\text{Breakeven price} = (\text{prevalent market price of diesel}) \times \left(1 + \frac{\Delta \text{AC} + \Delta \text{WC}}{(\text{total generation} \times \text{unit price of diesel})}\right)$$

where ΔAC indicates difference in the total annualized capital cost of diesel generator and biomass gasifier, while ΔWC indicates difference in the total operating cost of diesel generator and biomass gasifier system for a given plant load factor and capacity utilization factor. In other words, the definition of breakeven price of diesel is the price for which the total production costs of biomass gasifier-based generation and generation with 100% diesel are equal. The "unit price of diesel" appearing in the denominator of the second term in the bracket is the price used for calculation of annualized capital cost and working capital. Thus, the formula of Siemons [53] is implicit.

On the other hand, Nouni et al. [48] have defined breakeven price of diesel as the price for which the levelized unit cost of electricity (LUCE) from a biomass gasifier employing dual fuel engine is equal to the unit cost from a biomass gasifier employing 100% producer gas engine. On the basis of this definition, the formula used by Nouni et al. [48] for calculation of the breakeven price of diesel is:

$$\text{Breakeven price} = \frac{((LUCE_{hpg} \times E_o^{DF} - AC_C^{DF} - AC_{O\&M}^{DF})/(8760 \times CUF)) - C_{bm} S_{sbmc}^{DF} P^{DF}}{S_{spfc}^{DF} \times P^{DF}}$$

Notations are as follows: $LUCE_{hpg}$ – levelized unit cost of electricity for biomass gasifier with 100% producer gas engine; AC_C^{DF} – annualized capital cost for gasifier with dual fuel engine; $AC_{O\&M}^{DF}$ – annualized operating and maintenance cost for gasifier with dual fuel engine; C_{bm} – unit cost (per kg) of biomass; S_{sbmc}^{DF} – specific biomass consumption in a biomass gasifier with dual fuel engine; P^{DF} – rated power of dual fuel engine-generator; CUF – capacity utilization factor.

Siemons [53] has determined the "*feasibility region*" of the gasifier on the basis of breakeven price for diesel for a given capacity factor and biomass price. Quite obviously, the gasifier-based electricity generation is feasible in situation where the market price of diesel exceeds significantly the breakeven price. Although the economic feasibility for biomass gasifiers is lesser than charcoal gasifier (probably due to additional investments required for biomass preparation and storage), higher capacity system (>150 kW) could be economic. Despite this, Siemons [53] has noted that biomass gasifier could be economically feasible in certain sites where sufficient biomass supply is available at low costs. Reduction in the capital investment required for biomass gasifier could play crucial role in improving economy. Nouni et al. [48] have determined the breakeven price for diesel for a 20 kW gasifier with CUF of 25% and plant load factor of 50% as Rs. 32.05 per liter. For a 40 kW gasifier with same CUF and plant load factor, the breakeven price of diesel is Rs. 37 per liter. If we apply formula of Siemons [53] using model data of Nouni et al. [48], the breakeven price of diesel comes out to be Rs. 35.60 per liter. This is fairly close to the breakeven prices determined by Nouni et al. [48]. Based on the approach and results of Siemons [53] and Nouni et al. [48], on a whole, one can conclude that biomass gasifier-based generation becomes feasible for diesel costs above Rs. 35 per liter.

5.3. Feasibility of large scale units (500 kW to 5 MW)

Gasifiers with capacity 500 kW or higher fall in this category. The technology as well as economics of these systems has distinct differences from the small-scale stand-alone system. Major factors contributing to this are use of more efficient technology due to large capacity and possibility of meeting the fuel needs of the plant by having short rotation coppice [4,60–62], better capacity utilization factors as these units can meet the power need of a group of villages, higher plant load factor as these units can be connected to grid and possibility of selling power to the state government through power buy back policy. Commercial gasifiers available in the market are up to 500 kW only. Beyond this capacity, the fixed bed gasifiers (updraft and downdraft) suffer from limitations of oxygen channeling, high tar production, uneven temperature distribution that affect the overall stability of operation. Fluidized bed technology offers a viable solution for gasifier at capacities equal to or exceeding 5 MW. The fluidized bed technology is not commercialized in India. As noted earlier, the only option at these capacities is cogeneration projects with high pressure boilers and steam turbines. Bharadwaj [4] has reported a cost model for assessment of economic feasibility of biomass gasifiers at this scale of operation. The model parameters are listed in Table 14. In addition to annualized capital costs of gasifier and its operation, this model also accounts for transportation cost of biomass. At about some specific fuel consumption rate as low- to medium-scale gasifier, the 5 MW unit is expected consume 150–200 tons per day of biomass. Obviously, this quality of biomass may not be available in a single village. Therefore collection and transportation of biomass from adjacent village becomes an additional cost factor. For capacity utilization factor of about 68.5% (corresponding to 6000 h per annum of operation), the biomass collection area is located with radius of 10 km with the plant location taken as center. Obviously, the contribution of transportation cost factor to overall operational cost increases as the capacity of the plant increases. For example, for 5 MW capacity plant, the annual transportation costs amount to more than Rs. 1 crore (Rs. 10 million), if the overall plant efficiency is 20%. However, a marginal improvement in the efficiency to 25% can drastically reduced this cost to about Rs. 25 lakh (Rs. 2.5 million). Typically, the share of transportation costs increases from 5 to 15% as the capacity increases from 500 kW to 10 MW. The levelized unit cost of electricity produced from these units is quite small ~Rs. 2.75 per kWh (for 3 MW capacity), while power buy back is at Rs. 3 per kWh. Thus, the overall annual profit from the operation is Rs. 50 lakh (Rs. 5 million). However, as the capacity of plant increases, the transportation cost becomes a major factor and can offset the economy of scale-up making process unviable. Per calculation of Bharadwaj [4], the maximum profitable capacity of the biomass

Table 14
List of parameters (along with their typical values) for economic model of medium- to large-scale biomass gasifiers.

Parameter	Value
1. Plant capacity	500 kW to 5 MW
2. Capital cost of the plant	Rs. 40–70 million per MW
3. Debt ratio and interest	0.8 and 15%
4. Depreciation	10%
5. Biomass price	Rs. 1–3 per kg
6. Village area	200–400 ha
7. Process efficiency	15–25%
8. Biomass productivity	8–10 MT per hectare
9. Fraction of village biomass available for power production	20–40%
10. Concentration of villages	1 per 5 km^2
11. Tractor capacity	1–2 tons
12. Discount rate for capital investment and cash earning	15%
13. Plant load factor	68.5%
14. Buy back price of electricity	Rs. 3.01 per kWh

Source: [4].

gasification plant is 5 MW, beyond which the process becomes unprofitable. Other factor that comes into picture is the availability of biomass at steady prices. This may not be feasible in reality. Due to interrupted supply of biomass, the operation of the plant can affected, which would hamper the economy.

6. Case studies

About 24,500 villages in various states of India have been identified as remote villages where extension of grid electricity is not feasible. Therefore, all of these villages are proposed to be electrified with renewable energy options such as photovoltaics, micro-hydro, wind and biomass gasification. Among these options, biomass-based electrification stands higher in the Indian context as the biomass is uniformly spread in the country and biomass-based energy has a vital role in the rural life where agriculture is the principal activity [63–68]. Given below are some case studies of rural electrification by biomass gasification:

- *Hosahalli and Hanumanthenagara in Karnataka* [69–71]. Indian Institute of Science Bangalore has installed 20 kW gasifier in the two villages of Hosahalli and Hanumanthenagara (in Karnataka) in 1987 and 1994, respectively. The population of these villages is rather small (220 and 300, respectively) and agriculture was primary business. The gasifier installed in these villages have duel fuel generator with efficiency of about 23% woody biomass obtained from social forestry is used as fuel in the gasifier. The typical specific consumption of these gasifiers is 1.25 kg/kWh and the tariff is fixed at Rs. 3.34/kWh. Electricity was mainly used for domestic and street lighting, irrigation, drinking water supply and flour mills. The gasifiers were operated by locally trained people and managed by village committee. Electricity was generated and provided for 90% days in a year.
- *Odanthurai and Nellithurai in Tamil Nadu* [10,16,72]. Village *Panchayat* (or village committee) of Odanthurai (Tamil Nadu) has installed 9 kW capacity Ankur Gasifier for electricity required for water pumps for drinking water supply. With usage of biomass gasified electricity, the load on grid electricity has been reduced by over 70%. The gasifier operates on waste wood obtained from a local sawmill purchased at Rs. 0.3/kg. The efficiency of gasifier is typically 1.5 kg of wood/kWh. The number of consumers of this facility is approximately 4000 and the tariff is fixed at Rs. 30 per household per month. The installation at Nellithurai is similar as that in Odanthurai except that the village committee has decided to operate the streetlights on gasifier electricity. The specific fuel consumption and tariff structure is same as that in Odanthurai but the cost of biomass purchase is much higher at Rs. 800/ton dry wood.
- *Installation at Sundarbans in West Bengal* [10,49,73,74]. Two remote islands in Sundarbans, viz. Gosaba and Chottomollakhali have been electrified by West Bengal Renewable Energy Development Authority by installation of biomass gasifiers. The Gosaba Island located in 24 Paraganas district (115 km from Kolkata) has five units of 100 kW capacity. To meet the fuel wood needs, energy plantation has been carried out on 100 ha wasteland. The yield from this plantation is 10 tons of biomass per hectare per year. A cluster of five villages with total population of approximately 10,000 has been provided electricity from this installation. The generators are of dual fuel type, which consume 70% producer gas and 30% diesel at full load. The specific biomass consumption is 0.8 kg of dry wood/kWh and units are operated for 16 h each day. The tariff structure is Rs. 5.60/kWh for domestic users, Rs. 6.75/kWh for commercial users and Rs. 8/kWh for industrial users. The total capital cost of installation is Rs. 9.5 million, and this operation has provided direct and indirect employment to about 84 people.

  Similar installations have been made in the village of Chottomollakhali at Sundarbans with population of 9219 (total 1726 households). In June 2001, four units of 125 kW capacity each have been set up in this village at a cost of Rs. 14 million. The capacity utilization factor is 80% and operation of the plant lasts for 5 h each day. To meet the fuel needs of the gasifiers, plantation has been carried out in 10 ha land at a cost of Rs. 500,000. The biomass yield from this plantation is estimated at 5 tons ha^{-1} $year^{-1}$. The tariff structure is similar to the Gosaba Island and total number of beneficiaries from this venture are 225 (1 industry, 74 commercial and 150 domestic households).

7. Overview and conclusions

In this review, we have discussed the technical and economic aspects of decentralized power generation through biomass gasification in the Indian context. Demand for electricity in rural areas is growing at a rate of 7%. Total peak hour shortage of electricity is around 20,000 MW, while annual capacity addition is mere 3000 MW. India's power production potential is determined by coal-based thermal plants. However, coal deposits in India are rather localized in the eastern and northeastern regions of India. Addition of further capacity through coal-based thermal route would require transportation of coal to the plant site, which in turn would necessitate extension of railway network. During 11th plan, capacity addition of 75,000 MW is targeted, which is expected to fulfill the current gap between demand and supply of electricity in India. Despite this, extension of grid for accessing electricity is infeasible in some remote villages. In addition, high transmission and distribution losses add to difficulty of remote village electrification. Therefore, decentralized generation through locally available renewable energy sources is the only option for electrification of these villages.

There are strong arguments as how biomass gasification stands higher than other options for decentralized generation such as wind, photovoltaic and microhydro projects. The first argument is uniform and abundant distribution of biomass in the country; as well as availability at cheap rates throughout the year. Other arguments in favor of biomass gasification for decentralized generation are as follows [4,15,49,71,75]:

- *Proven technology*. The technology for the downdraft gasifier design has been well developed and demonstrated. There are several commercial manufactures of biomass gasifiers, who provide various capacity gasifiers at competitive rates. These gasifiers are usually coupled to dual fuel engine generators and the overall efficiency of the system is around 20%. Engines working on 100% producer gas are under development. These engines are likely to reduce the cost of generation even further.
- *Flexibility of installation and operation*. Biomass gasifiers can be installed at practically any village where sufficient biomass is available annually to ensure smooth operation. The duration of operation of gasifier is highly flexible. Low loads and low capacity utilization in rural areas is another hurdle in operation of ant renewable energy system. However, this problem can be overcome for biomass gasification-based system as their operational hours are highly flexible. Moreover, the overall operation of biomass gasification system is very simple. It is quite possible to train villagers (with qualification of HSC/SSC/I.T.I. diploma) for operation of the plant. Maintenance and servicing spare part replacement is also relatively easy than other options for renewable energy.
- *Social and environmental benefits*. Biomass gasification-based decentralized generation is likely to create employment opportunities in rural areas. These include the requirement of skilled/semi-skilled labor for operation and maintenance of gasifier

plants. In addition, plantation of energy crops in wasteland is also going to prevent the rapid degradation. Another important benefit of biomass gasification-based generation is reduction in CO_2 emission. It is estimated that replacement of each kilowatt-hour of coal-based electricity by biomass gasification-based electricity is likely to reduce CO_2 emission by 1 kg. Thus, biomass-based gasification helps in mitigation of green house gas emissions and problems related to it (such as global warming).

Successful implementation of decentralized village electrification, program in Karnataka, Tamil Nadu and West Bengal has clearly demonstrated feasibility of this option. However, actual installed capacity is much lower than the estimated potential. Thus, the biomass energy potential remains mostly unexploited. Following actions plan is recommended for enhancing the effective utilization of this vast energy resource [22,23,49,52,75,76]:

1. Large production of gasifier at competitive rates with engines working on 100% producer gas with establishment of design guidelines, performance standards and testing and certification. Development of "energy system package", which would enhance production, installation, operation and maintenance.
2. Enhancement of the load factor or capacity utilization factor by incorporating other commercial and industrial activities in the gasifier load, in addition to domestic and street lighting.
3. Encouragement of NGOs and other community-based organizations to act as energy service companies. These companies will be responsible for operation and maintenance of gasifier. Direct purchase of fuel biomass from individual villagers will provide them livelihood earning opportunity.
4. Subsidizing of the capital cost of gasifier will provide additional boost. Additional financing of working capital (as soft loans) for running the gasifier is also required. Regular information and awareness programs should be conducted to convince the rural population about the potential of gasifier-based generation. This will increase the number of local consumers, and hence, the cash flow central regulation of the tariff structure is also required through an appropriate policy.

References

[1] Ministry of Power, Government of India (website: http://powermin.nic.in).
[2] Central Electricity Authority, Ministry of Power, Government of India (website: http://www.cea.nic.in).
[3] Tripathi AK. Renewable energy development in India. In: Multiple choice questions on renewable energy. New Delhi: TERI Press; 2008. p. 1–12.
[4] Bharadwaj A. Gasification and combustion technologies of agro-residues and their application to rural electric power systems in India. PhD dissertation. Pittsburgh, PA, USA: Carnegie Mellon University; 2002.
[5] Sinha CS, Kandpal TC. Decentralized vs grid electricity for rural India: the economic factors. Energy Policy 1991;19(5):441–8.
[6] Chaurey A, Ranganathan M, Mohanty P. Electricity access for geographically disadvantaged rural communities—technology and policy insights. Energy Policy 2004;32:1693–705.
[7] Bhattacharya SC. Energy access problem of the poor in India: is rural electrification a remedy? Energy Policy 2006;34:3387–97.
[8] Reddy AKN. Rural energy: goals, strategies and policies. Econ Polit Week 1999;34(49):3445–55.
[9] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in rural India: an approach towards identifying potential areas for decentralized power supply. Renew Sust Energy Rev 2008;12:1187–220.
[10] Hiremath RB, Kumar B, Balachandra P, Ravindranath NH, Raghunandan BN. Decentralized renewable energy: scope, relevance and applications in the Indian context. Energy Sust Dev 2009;13:3–9.
[11] Chopra SK. Energy policy for India: towards sustainable energy security in India in the 21st century. New Delhi: Oxford & IBH Publishing Co. Pvt. Ltd.; 2004.
[12] Reddy AKN, Subramanian DK. The design of rural energy centers. Indian Acad Sci Bangalore 1979;2(3):109–30.
[13] Ravindranath NH, Hall DO. Biomass energy and environment: a developing country perspective from India. Oxford: Oxford University Press (UK); 1995.
[14] Ravindranath NH, Rao U, Natarajan B, Monga P. Renewable energy and environment: a policy analysis for India. New Delhi: Tata McGraw Hill; 2000
[15] Banerjee R. Comparison of options for distributed generation. Energy Policy 2006;34:101–11.
[16] Biomass booklet. New Delhi: Ministry of New and Renewable Energy, Government of India; 2005.
[17] Singh NP. Overview of renewable energy in India. In: 25 years of renewable energy in India. New Delhi: Ministry of New and Renewable Energy; 2007. p. 1–16.
[18] Nouni MR, Mullick SC, Kandpal TC. Techno-economics of micro-hydro projects for decentralized power generation in India. Energy Policy 2006;34:1161–74.
[19] 25 years of renewable energy in India. New Delhi: Ministry of New and Renewable Energy; 2007.
[20] Meshram JR, Mohan S. Biomass power and its role in distributed power generation in India. In: 25 years of renewable energy in India. New Delhi: Ministry of New and Renewable Energy; 2007. p. 109–34.
[21] Ministry of Coal (annual report, 2007–08, website: http://coal.nic.in). New Delhi; 2008.
[22] Ghosh D, Sagar A, Kishore VVN. Scaling up biomass gasifier use: applications, barriers and interventions. Paper no. 103 (climate change series). Washington: World Bank Environment Department; 2004.
[23] Jain BC. Commercialising biomass gasifiers: Indian experience. Energy Sust Dev 2000;IV(3):72–82.
[24] McKendry P. Energy production from biomass (Part 1): overview of biomass. Bioresource Technol 2002;83:37–46.
[25] McKendry P. Energy production from biomass (Part 3): gasification technologies. Bioresource Technol 2002;83:55–63.
[26] Li X. Biomass gasification in circulating fluidized bed. PhD dissertation. Vancouver, Canada: University of British Columbia; 2002.
[27] Kishore VVN, editor. Renewable energy engineering & technology: a knowledge compendium. New Delhi: TERI Press; 2008.
[28] Beenackers AACM, Maniatis K. Gasification technologies for heat and power from biomass. In: Bridgwater AV, editor. Biomass gasification and pyrolysis: state-of-the-art and future prospects. Newbury: CPL Press; 1997. p. 24–52.
[29] Beenackers AACM. Biomass gasification in moving beds. A review of European technologies. Renew Energy 1999;16:1180–6.
[30] Kohli S, Ravi MR. Biomass gasification for rural electrification: prospects and challenges. SESI J 2003;13:83–101.
[31] Tijmensen MJA, Faaij APC, Hamelinck CN, van Hardeveld MRM. Exploration of the possibilities for production of Fischer–Tropsch liquids and power via biomass gasification. Biomass Bioenergy 2002;23:129–52.
[32] Faaij A, van Ree R, Waldheim L, Olsson E, Oudhuis A, van Wijk A, et al. Gasification of biomass wastes and residues for electricity production. Biomass Bioenergy 1997;12:387–407.
[33] Hebden D, Stroud HJF. Coal gasification processes. In: Elliott MA, editor. Chemistry of coal utilization. New York: John Wiley and Sons; 1981.
[34] Liu P, Guo XF, Wu CZ, Chen Y, Arai N. Gasification characteristics of biomass wastes in fluidized bed gasifier. J Propul Power 2000;16:606–8.
[35] Mansaray KG, Ghaly AE, Al-Taweel AM, Hamdullahpur F, Ugursal VI. Air gasification of rice husk in a dual distributor type fluidized bed gasifier. Biomass Bioenergy 1999;17:315–32.
[36] Narvacz I, Orio A, Aznar MP, Corella J. Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Ind Eng Chem Res 1996;35:2110–20.
[37] Ergudenler A, Ghaly AE, Hamdullahpur F, Al-Taweel AM. Mathematical modeling of a fluidized bed straw gasifier. Part I. Model development. Energy Source 1997;19:1065–84.
[38] Bilodeau J-F, Therien N, Proulx P, Czernik S, Chornet E. A mathematical model of fluidized bed biomass gasification. Can J Chem Eng 1993;71:549–57.
[39] Yin XL, Wu CZ, Zheng SP, Chen Y. Design and operation of a CFB gasification and power generating system for rice husk. Biomass Bioenergy 2002;23:181–7.
[40] Garcia-Ibanez P, Cabanillas A, Sanchez JM. Gasification of leached *orujillo* (olive oil waste) in a pilot plant circulating fluidized bed reactor—preliminary results. Biomass Bioenergy 2004;27:183–94.
[41] Kersten SRA, Prins W, van der Drift A, van Swaaij WPM. Experimental fact finding in circulating fluidized bed biomass gasification for ECN's 500 kW_{th} pilot plant. Ind Eng Chem Res 2003;42:6755–64.
[42] Corella J, Sanz A. Modeling circulating fluidized bed biomass gasifiers: a pseudo-rigorous model with stationary state. Fuel Process Technol 2001;86:1021–53.
[43] Liu H, Gibbs BM. Modeling NH_3 and HCN emissions from biomass circulating fluidized bed gasifiers. Fuel 2003;82(13):1591–604.
[44] Devi L, Ptasinski KJ, Janssen FJJG. A review of the primary measures for tar elimination in biomass gasification processes. Biomass Bioenergy 2003;24:125–40.
[45] Narvaez I, Corella J, Orio A. Fresh tar (from a biomass gasifier) elimination over a commercial steam-reforming catalyst. Kinetics and effect of different variables of operation. Ind Eng Chem Res 1997;36:317–27.
[46] Milne TA, Evans RJ. Biomass gasification "tars": their nature, formation and conversion. Report no. NREL/TP-570-25357. Golden: NREL; 1998.
[47] Neeft JPA, Knoef HAM, Onaji P. Behavior of tars in biomass gasification systems. Tar related problems and their solutions. NOVEM report no. 9199. The Netherlands: EWAB; 1999.
[48] Nouni MR, Mullick SC, Kandpal TC. Biomass gasifier projects for decentralized power generation in India: a financial evaluation. Energy Policy 2007;35:1373–85.
[49] Ghosh D, Sagar AD, Kishore VVN. Scaling up biomass gasifier use: an application specific approach. Energy Policy 2006;34:1566–82.

[50] Tripathi AK, Iyer PVR, Kandpal TC. A financial evaluation of biomass gasifier based power generation in India. Bioresource Technol 1997;61:53–9.
[51] Jorapur RM, Rajvanshi AK. Development of a low density biomass gasification system. In: Proceedings of 28th international energy conservation engineering conference, vol. 2; 1993. p. 443–8.
[52] Kishore VVN, Bhandari PM, Gupta P. Biomass energy technologies for rural infrastructure and village power—opportunities and challenges in the context of global climate change concerns. Energy Policy 2004;32:801–10.
[53] Siemons RV. Identifying a role for biomass gasification in rural electrification in developing countries: the economic perspective. Biomass Bioenergy 2001;20:271–85.
[54] Nouni MR, Mullick SC, Kandpal TC. Techno-economics of small wind electric generator projects for decentralized power supply in India. Energy Policy 2007;35:2491–506.
[55] Nouni MR, Mullick SC, Kandpal TC. Photovoltaic projects for decentralized power supply in India: a financial evaluation. Energy Policy 2006;34:3727–38.
[56] Kandpal TC, Garg HP. Financial evaluation of renewable energy technologies. New Delhi: McMillan India Ltd.; 2003.
[57] Jorapur RM, Rajvanshi AK. Operating experience and economics of a 15 kVA genset-gasifier system running on chopped sugarcane leaves. In: Paul PJ, Mukunda HS, editors. Recent progresses in biomass gasification and combustion. Bangalore: Interline Publishing; 1993.
[58] Kapur T, Kandpal TC, Garg HP. Electricity generation from rice husk in Indian rice mills: potential and financial viability. Biomass Bioenergy 1996;10:393–403.
[59] Ghosh S, Das TK, Jash T. Sustainability of decentralized wood fuel-based power plant: an experience with India. Energy 2004;29:155–66.
[60] Mitchell CP, Bridgwater AV, Sterens DJ, Toft AJ, Watters MP. Technoeconomic assessment of biomass to energy. Biomass Bioenergy 1995;9(1–5):205–26.
[61] Bridgwater AV. The technical and economic feasibility of biomass gasification for power generation. Fuel 1995;74(5):631–53.
[62] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass Bioenergy 2005;28:35–51.
[63] Ramchandra TV, Joshi NV, Subramsnian DK. Present and prospective role of bioenergy in regional energy system. Renew Sust Energy Rev 2000;4:375–430.
[64] Gupta CL. Role of renewable energy technologies in generating sustainable livelihood. Renew Sust Energy Rev 2003;7:155–94.
[65] Demirbas AH, Demirbas I. Importance of rural bioenergy for developing countries. Energy Conserv Manage 2007;48:2386–98.
[66] Varun, Singhal SK. Review of augmentation of energy needs as renewable energy sources in India. Renew Sust Energy Rev 2007;11:1607–15.
[67] Mukunda HS. 100% of energy from renewable—is this an achievable goal or an important slogan? (http://cgpl.iisc.ernet.in).
[68] Ravindranath NH, Balachandra P. Sustainable bioenergy in India: technical, economic and policy analysis. Energy 2009; doi:10.1016/j.energy.2008.12.012.
[69] Sridhar G, Sridhar HV, Basawaraj SMS, Somsekhar HI, Dasappa S, Paul PJ. Case studies on small scale biomass gasifier based decentralized energy generation system (http://cgpl.ernet.in/site/portab0/publication/Nationalconf/caseStudiesOnSmall BiomassGasifier.pdf).
[70] Somashekhar HI, Dasappa S, Ravindranath NH. Rural bioenergy centers based on biomass gasifiers for decentralized power generation: case studies of two villages in Southern India. Energy Sust Dev 2000;4:55–63.
[71] Ravindranath NH, Somashekhar HI, Dasappa S, Reddy CNJ. Sustainable biomass power for rural India: case study of biomass gasifier for village electrification. Curr Sci 2004;87(7):932–41.
[72] Abe H. Summary of biomas power generation in India (http://www.plants.uwa.edu.au/home/research/research_centres/ergo/students/hitofumi_abc). Crawley: Japan International Cooperation Agency; 2005.
[73] Mukhopadhyay K. An assessment of biomass gasification based power plants in Sunderbans. Biomass Bioenergy 2004;27:253–64.
[74] Mukhopadhyay K. A review of the socio-economic and environmental benefits of biomass gasification based plants: lessons from India. In: Warmer SF, editor. Progress in biomass and bioenergy research. New York: Nova Science Publishers; 2006.
[75] Mukunda HS. Low cost, high efficiency biofuel-to-electricity: past and future (http://cgpl.iisc.ernet.in).
[76] Mukunda HS, Dasappa S, Paul PJ, Rajan NKS, Sridhar G, Sridhar HV, et al. Thermo-chemical conversion of biomass—a retrospective and perspective. I.I.Sc. Bangalore (http://cgpl.iisc.ernet.in).
[77] Reference material. I.I.Sc. Bangalore: International Training Program on Biomass Technologies; Combustion Gasification and Propulsion Laboratory; April 2001.
[78] Biomass atlas of India. CGPL: Indian Institute of Science, Bangalore (http://cgpl.iisc.ernet.in).
[79] I.I.Sc. gasifiers installed in India and overseas (PDF document). I.I.Sc. Bangalore: International Training Program, Combustion Gasification and Propulsion Laboratory; April 2001 (http://cgpl.iisc.ernet.in).
[80] http://www.ankurscientific.com.
[81] Energy development. In: Economic review. Department of Planning and Economic Affairs, Government of Kerala; 2003.